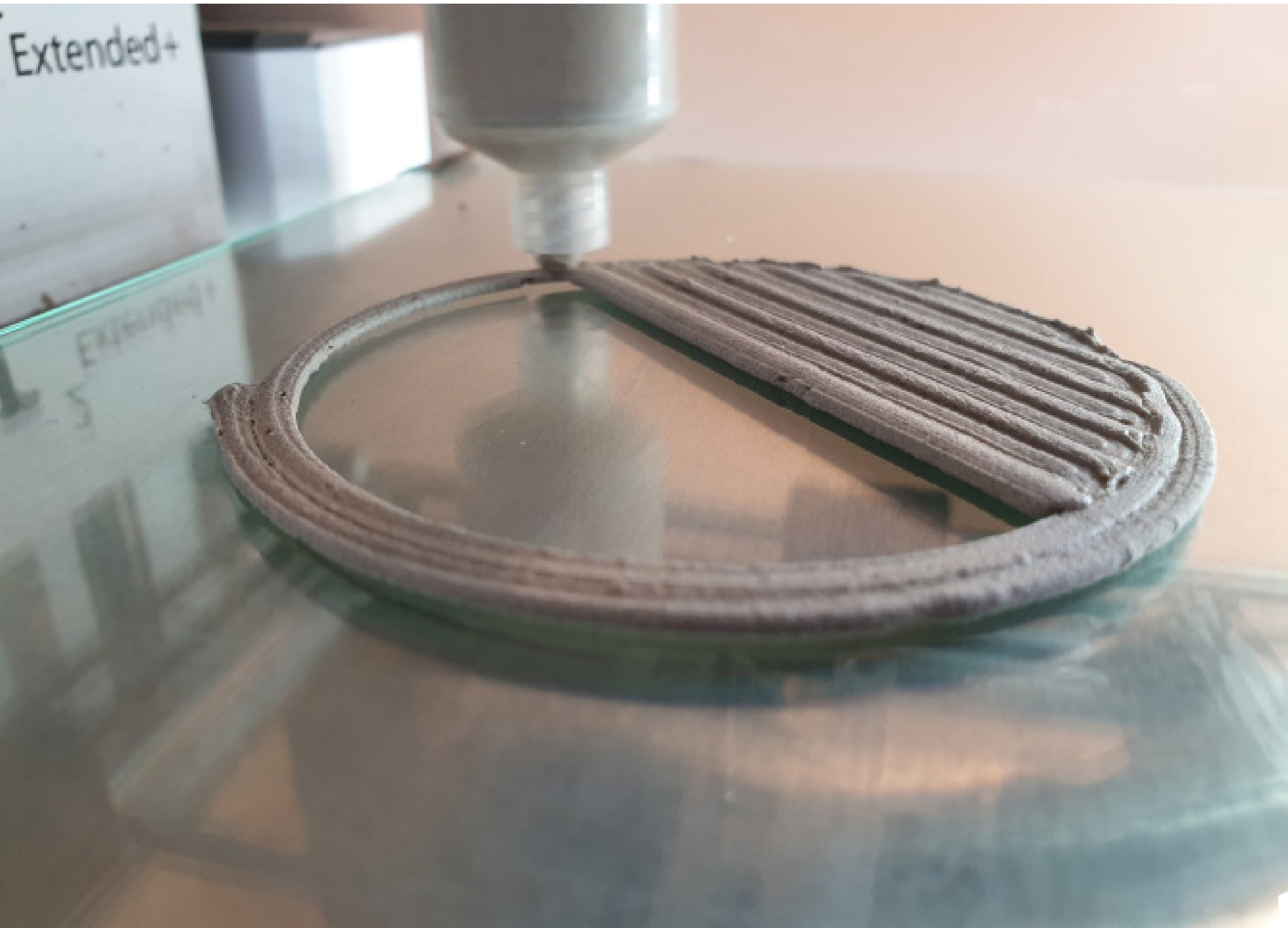
Towards a Circular Economy:

Exploring the applications of 3D printing with mussel shell waste



MASTER THESIS
Edwin van Tongeren

COLOPHON

Towards a Circular Economy;
Exploring the applications of 3D printing with mussel shell waste.
E. van Tongeren
06-03-2020

Master Thesis
Integrated Product Design
Industrial Design Engineering
Delft University of Technology

Supervisory Team:
Zjenja Doubrovski (chair)
Mariet Sauerwein (mentor)

Summary

This master thesis is the result of a graduation project for the Integrated Product Design master at the Delft University of Technology. The project continues on the research by Mariet Sauerwein and Zjenja Doubrovski, and on the master thesis by Joost Vette. These researches developed a recycled and biobased material from mussel shells and sugar water and proved its potential as AM material. This material is made from a local waste stream and can be recycled after use.

This project continued with the mussel shell powder, but used sodium alginate (instead of sugar) as a binder, based on recommendations of the aforementioned researches. Sodium alginate allows cross-linking and therefore has the potential for applications that need to be water-resistant. After use, sodium alginate can be reversibly cross-linked, to keep the possibility of recycling. The goal of this thesis is "to design and create a 3D printed product with mussel shell-alginate paste that lasts at least 2 life cycles". To achieve this goal, 2 research questions were formulated:

1. *What are the printing properties and material experiences of mussel-sodium alginate paste, and how can we optimize them?*

2. *How can this biobased material be used for suitable and meaningful applications in a CE?*

The project is based on the Material Driven Design method (Karana et al., 2015), with added Delft Design Guide methods and circular economy strategies. After the Literature phase, it was decided to test and optimize the material's viscosity. It was found that a lower viscosity was needed to improve the maximum achievable print height. To be able to use this viscous paste, a new setup with lower resistance was developed. After the AM material and AM setup were adapted to each other, the way the material was experienced had been tested. The MA2E4 toolkit was used for the experiential characterization user test, whose conclusion served as brainstorm input for the ideation phase. Approximately 40 ideas were generated, which in different steps were converted to 3 concepts. This selection was made based on the wishes and requirements with tools such as C-box and Harris profile.

The 'patient-specific braces' were chosen as the most valuable concept using Harris profile. However, a discussion with orthopedist Wybren ten Cate concluded that the material is currently too weak and slow-drying to have great potential for this concept. Based on the Harris Profile, the 'circular gardening' concept was chosen instead. Its value for additive manufacturing was increased by upgrading the concept to 'parametrically designed plant-specific planters'; AM is used to design planters adapted to the unique care different plants require. Because this makes gardening way easier, it was designed for people who lack the skills or time to keep their plants alive. After several printing tests, this resulted in a 3-component prototype; visual outer pot; nutrients providing inner pot and water dispensing funnel. These prototypes can be used to showcase and validate the possibilities of this bio-based material.

Table of Contents

Chapter 1

Project description

1.1 Introduction

A circular economy (CE), a concept introduced by the British environmental economist David Pearce in 1990, is an economic system aimed at the elimination of waste and the continual use of resources (Pearce, 1990). A CE emphasizes the benefits of recycling residual waste materials. As the Ellenmacarthur foundation describes, it is based on three principles: Designing out of waste and pollution materials, keeping products and materials in use, and regenerating natural systems (MacArthur, 2013).

Additive manufacturing (AM) is a technology with great potential to support the circular economy, due to the opportunities it provides to save resources during production (Gebler, 2014). Furthermore, AM is able to support multiple product life cycles and enables distributed manufacturing, because it can be used locally, on-demand and for small batches (Vette, 2018). Distributed production supports a CE because it can use local waste, it cuts transportation emission and creates opportunities to extend the lifespan of products, for example by repairing it or giving the product an update (Sauerwein et al., 2019).

Additive manufacturing (AM), colloquially known as 3D printing, is a manufacturing technique which is known for its freedom of design, mass customisation, fast prototyping, waste minimisation and ability to create complex structures (NGO, 2018). The printing process is called additive manufacturing because it (usually) successively adds material layer by layer to create a three-dimensional object retrieved from a computer-aided model. The AM technology used in this project is based on material extrusion; Fused filament fabrication (FFF), often called fused deposition modelling (FDM). Over the last couple of years, FDM proved to have the potential for a wide variety of applications. FDM with plastics have been around for some time, but FDM with other materials (like concrete and clay) emerges at a rapid pace. However, the currently used materials for FDM are generally not locally sourced and their recycling options are limited (Sauerwein et al., 2018).

This thesis continues on research addressing this problem. That research has shown that mussel shells, a big and growing waste stream, can be converted into a printable material (Sauerwein et al., 2018). Not only are mussel shells abundant, but they can be used to create a renewable paste as well, which makes it particularly suitable for the CE (Vette, 2018). Because of the high concentration of calcium carbonate in this mussel powder, it appeared to have great printing properties when combined with a binder like sugar water. When submerging it in water, this paste can be recycled without the loss of material quality, which makes multiple life cycles possible (Vette, 2018). This material can be sourced, manufactured and recycled locally. The obtained closed material loop forms the basis of a CE, as it is a system in which resource loops are closed (Bocken et al., 2016). This material differs from conventional extrusion materials (such as ABS & PLA) because it is a paste. Pastes harden by drying (evaporation of water) instead of solidifying (phase transition).

To facilitate recycling even more, this thesis combines ground mussel shell powder with sodium alginate (instead of sugar water) which allows reversible crosslinking of the binder (Kilan, 2014). In this way material properties can be improved and the material becomes water-resistant, in contrast to the sugar water paste. Therefore, applications that come in contact with water are possible design options as well. It is known that mussel shell-alginate paste can be used for 3D-printing, but the exact printing properties are still unknown. Therefore, the goal of this project will be to find a suitable application for this material that fits into a circular economy. More specifically; “to design and create a 3D printed product with mussel shell-alginate paste that lasts at least 2 life cycles”. In this thesis, we discuss the mussel shell-alginate paste as an AM material, describe the consequences and limitations of printing with this biobased material, and search for meaningful applications of this material to serve the circular economy.

1.2 Problem definition

Although 3D printing with mussel shell powder and sodium alginate has never been experimented with before, there are some examples of AM using a paste for printing products that might help to find suitable applications for printing an alginate-mussel paste. For example, cement and concrete is being used to 3D print houses (Hager, 2016; Malaeb, 2015), potteries and artist use clay to 3D print artworks and ceramics (Bengisu, 2013; van Herpt, 2019) and alginate is used to create Bio inks for 3D bioprinting (Axpe et al., 2016). The researches that come closest to the current project are Vette (2018) and Sauerwein et al (2018). They developed a printable mussel-sugar-water paste, which is used to create sustainable lighting (Vette, 2018). This are the researches this project is based on.

While these examples may provide some useful similarities with the printing of mussel-alginate, a lack of literature on the printing of mussel-alginate means that the complications of printing this biobased material have yet to be examined. This lack of literature means that the material is not yet fully defined; both the composition of the material and the parameters of the printing process need to be determined. As a result, the material properties are unknown and it remains a question for which applications the material would be a good match. Therefore, the first knowledge gap is the *printing properties and material experience of the mussel-alginate paste*. When these are known an iterative process starts in search for suitable applications. This leads to filling the second knowledge gap; *how can this biobased material be used for suitable and meaningful applications in a CE?*

1.3 Research questions

The two aforementioned knowledge gaps are converted into two research questions, each with their own sub-questions.

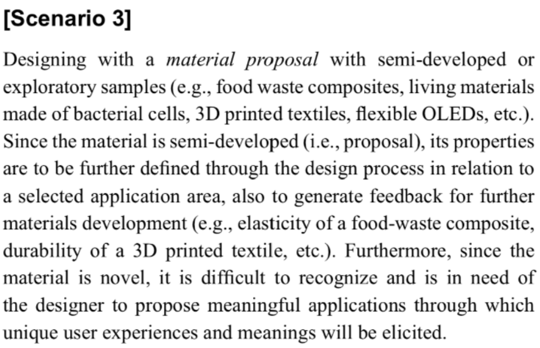
What are the printing properties and material experiences of 'mussel shell-sodium alginate' paste, and how can we optimise them?

- Is the paste printable (does it extrude) and stable (does it collapse)?
- How is the material experienced?
- What can we change to optimize these printing properties (printability and stability) and material experience?

How can this biobased material be used for suitable and meaningful applications in a CE?

- How to use the experiential characterisation conclusions to get to meaningful applications?
- What design principles can be used so that these applications also suit a CE?
- What other steps have to be taken into account to print this application?

These questions will be answered throughout the project. Section 9.3 (evaluation) provides the answers to these questions in 1 overview.



[Scenario 3]

Designing with a *material proposal* with semi-developed or exploratory samples (e.g., food waste composites, living materials made of bacterial cells, 3D printed textiles, flexible OLEDs, etc.). Since the material is semi-developed (i.e., proposal), its properties are to be further defined through the design process in relation to a selected application area, also to generate feedback for further materials development (e.g., elasticity of a food-waste composite, durability of a 3D printed textile, etc.). Furthermore, since the material is novel, it is difficult to recognize and is in need of the designer to propose meaningful applications through which unique user experiences and meanings will be elicited.

Fig. 1. Scenario 3 MDD method

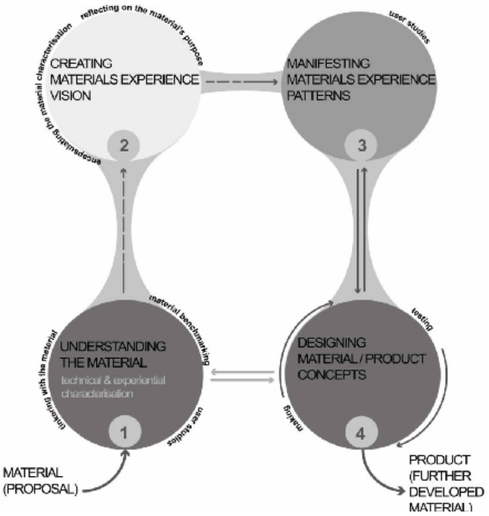


Fig. 2. Main steps MDD method

1.4 Purpose

As discussed in the intro, the purpose of this project is *"to design and create a 3D printed product with mussel shell-alginate paste that lasts at least 2 life cycles"*. This means that an application needs to be found for the material, which is still in development, while ensuring that the material remains usable after multiple life cycles. For this project, the material properties and possible applications are considered to be interdependent. The properties of the materials, influence what applications it can be used for. In turn, possible applications can inform the requirements for the material. Therefore, these two topics will be addressed iteratively. A variety of 3D printing parameters can be modified that each has an effect on the material properties. These include, for example, nozzle size, printing speed, and layer thickness. Furthermore, the properties of the material itself can be fine-tuned, such as viscosity. Low viscosity could be desired for easier extrusion when printing but could cause the 3D printed parts to collapse. The effect of these and other parameters need to be accurately tested, while constantly considering how the resulting materials and materials structures could be applied in a product. The end result of this project will be a design of a 3D printed product, a printable mussel-shell material, accompanied by suitable 3D printing process parameters for the application and material.

1.5 Methodology

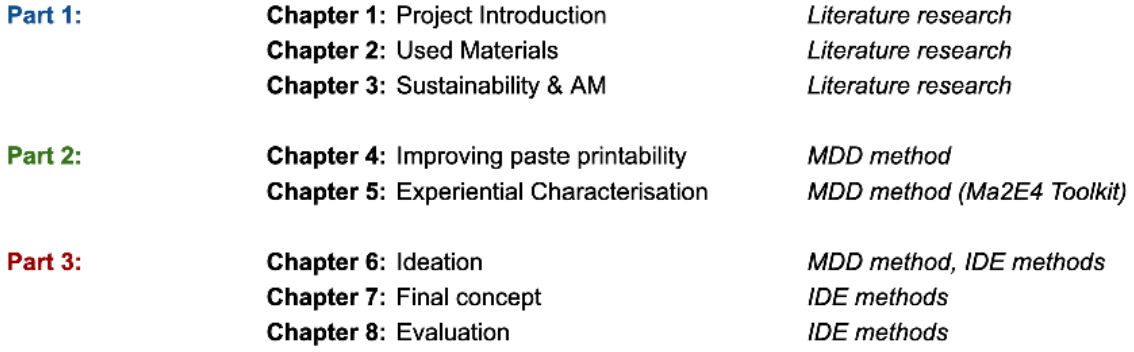
The basis of this project lies in the Material Driven Design Method (MDD). Karana et al. (2015) describe three scenarios for which MDD is suitable. The third scenario (see figure 1) matches this project, since both the material and the samples are not yet fully developed. The main steps from this method are shown in the illustrative case shown in figure 2.

Of this four-step method (Karana et al., 2015), the first and the last step are the most suitable for this project. Step 1 (immediately after the material proposal) is about understanding the material, which is done by experiential (and technical) characterisation. For the experiential characterisation, the Ma2E4 toolkit is used (materialsexperiencelab) to examine the material experience. The last step of the scenario is important for this project because it examines the designing of the product concepts using creative sessions.

In this third phase of the project (ideation and conceptualisation) some IDE methods from the Delft Design Guide will be used, such as brainstorming and harris (Boeijen et al., 2017). The figure below shows in which chapters the aforementioned methods will be used. Previous research (Vette, 2018) concluded that the 2nd and 3rd MDD step are not very usefull for a projet like this, which is why those will not be used.

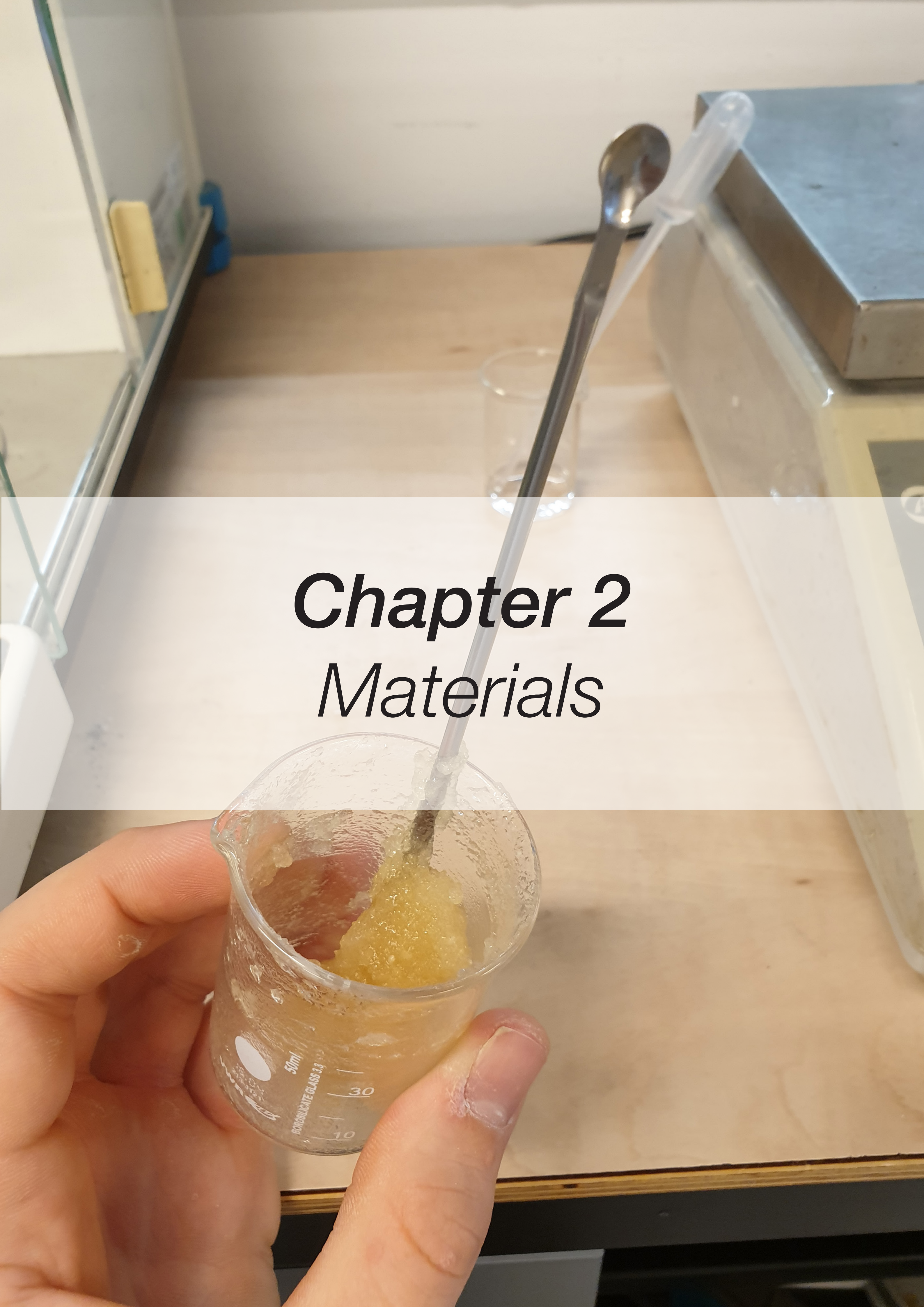
1.6 Used abbreviations

AM:	Additive Manufacturing
CE:	Circular Economy
MDD:	Material Driven Design method
N-a:	Sodium alginate
CaCO3:	Calcium carbonate
FDM:	Fused deposition modeling
FFF:	Fused filament fabrication
IDE:	Industrial Design Engineering



Part 1:	**Chapter 1:** Project Introduction	*Literature research*
	Chapter 2: Used Materials	*Literature research*
	Chapter 3: Sustainability & AM	*Literature research*
Part 2:	**Chapter 4:** Improving paste printability	*MDD method*
	Chapter 5: Experiential Characterisation	*MDD method (Ma2E4 Toolkit)*
Part 3:	**Chapter 6:** Ideation	*MDD method, IDE methods*
	Chapter 7: Final concept	*IDE methods*
	Chapter 8: Evaluation	*IDE methods*

Fig. 3. Methods used in this project



Chapter 2

Materials

2.1 Introduction

This chapter provides a more detailed explanation of the materials that are used in this project. Firstly, we review how mussel shells end up as waste in the Netherlands. Secondly, the main component of mussel shells, calcium carbonate, will be elaborated on, as well as the used binder; sodium alginate. Thirdly, the used printer setup and paste preparation process will be discussed, and the chapter wraps up with current sodium alginate applications and insights about introducing new sustainable materials.

2.2 Mussel shells in the Netherlands

Vette (Vette, 2018) describes how mussel shells are starting to become an immense waste stream in the Netherlands; approximately 90 million kg of mussels are sold in Zeeland annually, of which 50 million kg are cultivated in the Netherlands (Nederlands Mosselbureau, 2019; Mosselen.nl, 2019). Of these mussels, 40% of the weight consists off the shell (Hamester, 2012). Not all mussels that are sold in Zeeland are cultivated in the Netherlands as well because Yerseke in Zeeland is home to the only mussel auction in the world (Mosselen.nl, 2019). After mussels are bought at the auction a part of them gets processed (taken out of their shell) locally. The companies retailing processed mussels dump the mussel shell waste material (figure 4). Since all seven Dutch mussel processing companies (Verroen, 2018) are located in Zeeland, this is where most of the waste material is. For that reason, Vette (Vette, 2018) took Zeeland as local manufacturing area. Since the mussel shell waste on the coasts of Zeeland keeps increasing, this project takes Zeeland as local manufacturing area as well.

In May 2019, the biggest Dutch (Barbé) and German (Leuschel) mussel processing companies merged, creating the biggest mussel processing company: Aquamussel. Their mussels will be processed in their expanded factory in Yerseke, creating the biggest mussel processing factory worldwide. This means that, starting from the mussel season 2019, the annual amount of dumped mussel shell waste in Zeeland will grow as well (Bevelander, 2019).

Mussel shells are seen as waste that is not suitable for composting (Milieu Centraal gft, 2016). There are, however, some other purposes for the reuse of mussel shells. As Vette mentions (Vette, 2018), some mussel shells are used for the cultivation of oyster larvae, fertilizers or soil alkalizers in agriculture (Marlborough Express, 2014) or, on a small scale, for art. In Australia, the waste mussel shells are used to form a reef foundation (figure 5), in hopes of restoring the shellfish reefs (ABC.net, 2019). Sardinia uses crushed mussel shells to make useful products (figure 6) by using 3D printed molds (Webgate, 2017). In 2017, the EU started the Blue Shell project, in which coastal countries are looking for reuse purposes of waste mussel, crab and shrimp shells. Examples are bioactivities like functional foods development, food safety applications and plant health applications (Marinebiotech, 2017). Still, by far the biggest part of the shells ends up in a waste dump, mainly in Zeeland (see figure 4).

Fig. 4. Mussel shell waste (vliz.be)

Fig. 5. Australia uses shells to revive reefs (ABC.net, 2019)

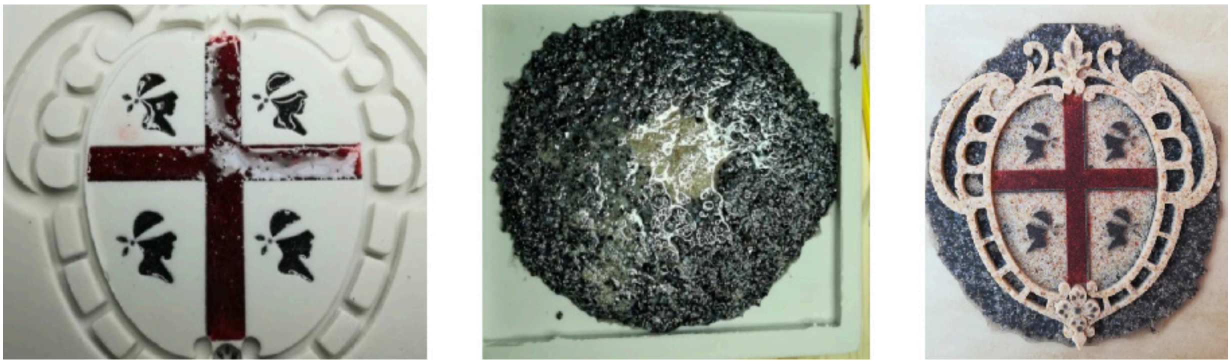


Fig. 6. Students and 'FLAG' in Sardinia turn mussel shells into products using 3D printed moulds (Webgate, 2017)

These mussel shells consist for 95-99% out of calcium carbonate (CaCO3). Because of the organic matrix it forms between the CaCO3 molecules, the strength of a mussel shell is at least 4 times higher than CaCO3 on its own (CES EduPack 2019). These internal structures might be interesting for this project because it can potentially be used to improve the strength of the 3D printed parts. However, Vette (Vette, 2018) described that turning amorphous calcium carbonate into crystallised CaCO3 is not fully understood yet (Fitzer, et al., 2016). Therefore he concluded that it is not possible to use this biomineralisation process for a project like this.

2.3.1 Sodium-alginate

Sodium alginate is a natural polysaccharide, which is extracted from the cell walls of brown seaweed (=marine brown algae, Phaeophyceae). Seaweed is one of the few raw materials which do not need irrigation water, pesticides, fertilizers, and cultivation land to grow. The function of alginate is to give flexibility to the seaweed. Alginates can be found in cold and mostly in troubled waters (molecularrecipes.com). On the west coast of the USA, the Macrocystis is used most often to extract sodium alginate while in Europe it is extracted from Laminaria and Ascophyllum, shown in figures 7 & 8. These algae consist of approximately 40% of alginate (of the dry matter of the plant). In Europe and USA the harvest happens naturally, but in China large-scale cultivation takes place. The early production of sodium alginates begun in the 20th century. The annual industrial production of alginates is estimated at 30.000 tons (Hay, 2013).

2.3.2 Production of sodium alginate

Figures 9 & 10 show schematic flowcharts of the production of sodium alginates. McHugh (1987) describes the production process of sodium alginate in 9-steps: The first step in the production of sodium alginate is the harvest of the seaweed (figure 7). To prevent the solution from becoming too thick for filtering in the next steps, the seaweed gets diluted with a large amount of water (step 2). A sodium carbonate solution is added and put to rest for 2 hours. The alginate dissolves to sodium alginate in a thick slurry (step 3). Since water is added in previous steps, this solution can be filtered (step 4), isolating the seaweed residue (step 5) from the sodium alginate solution (step 6).

Fig. 7. Harvest of Laminaria hyper borea (McHugh 2003).

Fig. 8. Left: Laminaria Hyperborea, right: Ascophyllum Nodosum (Seaweed.ie)

The next step is to precipitate the alginate from the sodium alginate solution, which can be done in two ways. The 'alginic acid process' is used for the production of high-quality alginic acid, since it diminishes calcium contamination. Calcium has a negative effect on the properties and functionality of the final sodium alginate (kimica-algin), which is why the 'alginic acid process' is most suitable in the scope of this project. In this process, acid is added to the sodium alginate solution creating an alginic acid gel (step 7). Since alginic acid does not dissolve in water, the water can be separated (step 8) and relatively solid alginic acid remains. Subsequently, alcohol and sodium carbonate is added, which (combined with the alginic acid) forms sodium alginate (step 9). The sodium alginate does not dissolve in the water and alcohol mixture, which is why it can be isolated from each other. The sodium alginate is dried and milled into a powder for sale (fao.org).

The process described above is executed on a large scale in countries like China and India. There are, however, no suppliers of sodium alginate in the Netherlands (only NEO-alginate). To keep the transportation emissions as low as possible it would be possible to turn to the only two sodium alginate producing companies in Europe; in Norway (Dupont) and France (Algaia), which both have sustainability as one of their main priorities. Recently, however, a new alginate-like material called Kaumera, can be sourced from sewage (Verdonk, 2019). This material really fits a CE and can in the future (when it is sold) possibly replace the sodium alginate since it has (almost) the same properties as alginate.

Fig. 9. Flowchart of the production of sodium alginate (McHugh, 1987)

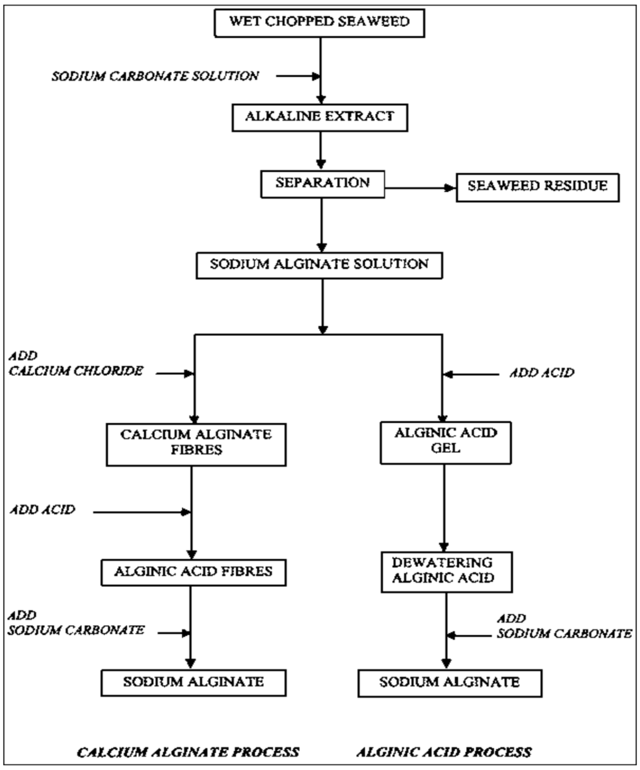
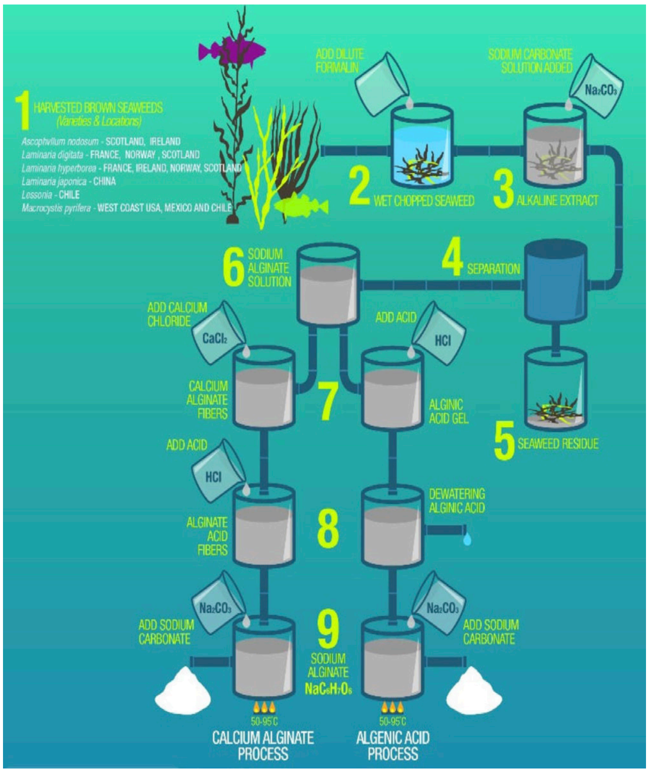


Fig. 10. Visualisation of the production of sodium alginate (Artmolds.com)



2.3.3 Sodium alginate as a binder

Sodium alginate is a ‘low viscous alginate’ (iopscience, 2018) which makes it suitable for FDM. The main reason, however, for using sodium alginate as a binder is its potential of reversible cross-linking. Crosslinking is creating the chemical bond of one polymer chain to another (Kilan, 2014). These bonds are covalent bonds or ionic bonds happening between either natural or synthetic polymers (Delaney, 2010). Cross-linking is used to make a change in the properties of polymers (Yang, 2000); it is not soluble in water anymore and the mechanical properties (like tensile strength) are improved because of the extra internal connections of Ca2+ bridge (Yang, 2000).

Crosslinking takes place when, for example, calcium ions are added to sodium alginate (Lin et al., 2005). The sodium ions are exchanged for calcium ions and the polymer becomes cross-linked; the calcium ions form double bonds with the alginate ions, making the material water-resistant (Yang, 2000). Figure 11 shows cross-linking with calcium chloride in a simplified figure (theorganicsolution.com). Alginates are ‘Thickeners’, but when divalent ions like calcium (Ca2+) are added they become a ‘Gellant’ because of the cross-linking. The ‘hydrogel’ that appears is a temperature stable gel between 0 and 100 °C, which is uncommon for gels (theorganicsolution.com).

The longer the sodium alginate is in contact with the calcium ions, the more Ca2+ bridges will be made and the more rigid the gel will become. Furthermore, the concentration of the calcium ions will determine if the gel will be temperature reversible (low concentrations) or not (high concentrations) (Pignolet et al., 1998). When the gel is not temperature reversible (which is the case in this thesis), the cross-links can be reversed in a bath filled with sodium ions. Figure 13 shows this chemical transition in a more detailed manner. Left part of this figure shows that during the crosslinking, calcium chloride is added to the strings of sodium alginate, causing the calcium ion to replace the two sodium ions. While the two sodium chloride ions are discarded calcium alginate is created. During this crosslinking, calcium forms highly stable complexes with alginate to form networks. To reverse this alginate crosslinking (right part in figure), a trisodium EDTA solution is added which exchanges the sodium-ions for the calcium ions (Delaney, 2010), which makes it water-soluble again.

When the mussel-alginate paste is created, reversible cross-linking should take place as well, since both alginate and calcium (carbonate) molecules (=mussel shells) are present. This process does not occur, however, due to the heterogeneous nature of the musselshell-alginate paste. Sodium alginate is very soluble in water (kimica-algin), but calcium carbonate is very poorly soluble in water (Frear, 1929). Figure 12 shows calcium carbonate solubility in water (Hart et al., 2011). Higher PH values decrease the solubility in water significantly. In the Netherlands, almost all municipalities have a minimum PH of 5.0 or higher (waterhardheid.nl). This matches with a solubility of 0.1 mg/L (figure 12), which is negligible. This means that when the binder (sodium alginate) dissolves in water, it sticks between the mussel powder grains because calcium carbonate is very poorly soluble. Therefore the sodium alginate does not react with the calcium carbonate from the mussel shells. Calcium chloride is water-soluble (CES EduPack), just like sodium alginate, and therefore reacts, which results in crosslinking.

Fig. 11. A simplified figure of cross-linking sodium alginate with calcium ions (theorganicsolution.com)

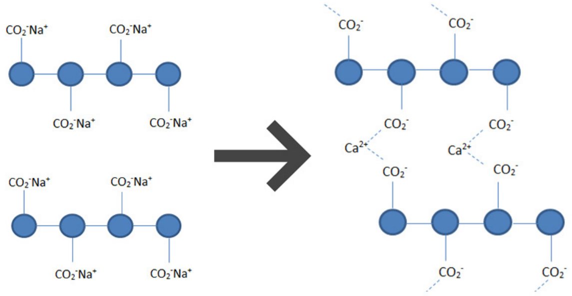
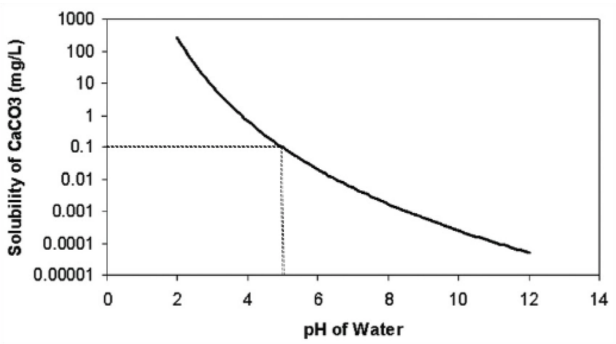


Fig. 12. Solubility of calcium carbonate (Hart et al., 2011)



2.3.4 Sodium alginate applications

The crosslinking described above has potential for this project since it allows us to design applications that frequently get in contact with water, like vases, flowerpots, and tableware. By exposing those waterproof applications to sodium ions, in this case a trisodium EDTA solution, they can still be used for a circular economy, which is the final goal of this project. This exact same property is the reason alginates are nowadays used for a wide variety of applications. Because alginates are excellent thickeners, gellants and stabilisers they are often used in food. Sodium alginate is used as stabiliser in (a.o.) yogurt, ice-cream, cheese and cream (Modernistpantry), it functions as a thickener and emulsifier for salad, pudding, jam, canned products, tomato juice, pastries, sauces, syrups, and toppings (molecularrecipes) and it is a hydration agent for bread, noodles, and frozen products. Furthermore, sodium alginates are used in textile printing, the pharmaceutical sector, cosmetics, lifecasting, prosthetics, welding rods, animal feed, and dental care as well (Wikipedia). Additionally, it is used for medical applications, like textiles and bandages with integrated calcium ions, which can be removed more easily than conventional ones since calcium is not soluble in water (Knill et al., 2004). Alginates are also used in drug delivery applications (Badwan et al., 1995; Tønnesen et al., 2002). Figure 14 gives an impression of the wide variety of applications sodium alginates are used for. More recently, alginates have been used for research projects. In lithium-sulfur batteries, the electrochemical and binding properties of alginate are applied in the preparation of sulfur cathodes with lower resistance (Bao et al., 2013). In gastronomy, alginates have been used for multiple years, but one of the most recent advances is spherification; reversible cross-linking alginate beads in a bath, for example to create perfect droplet-shaped food, see figure 15 (the organic solution).

An application that comes close to the scope of the thesis is the 3D printing of sodium alginate, in order to cross-link the material right after the print, shown in figure 16 (Tabriz et al., 2015). Firstly, Tabriz et al. printed partially cross-linked alginate hydrogel on a porous membrane bed where the alginate is able to keep its shape. Further cross-linking takes place when the printing bed is lowered and the print is submerged into a CaCl2 bath, creating a better foundation for the upcoming layers. Finally, upward diffusion of the calcium ions starts to cross-link the partially cross-linked interface layers (Tabriz et al., 2015). This research might be of importance for this thesis since it shows a possibility to keep the alginate fluid enough to be printable, but at the same time enforce it right after it is printed to be stable enough to avoid collapsing of the printed product.

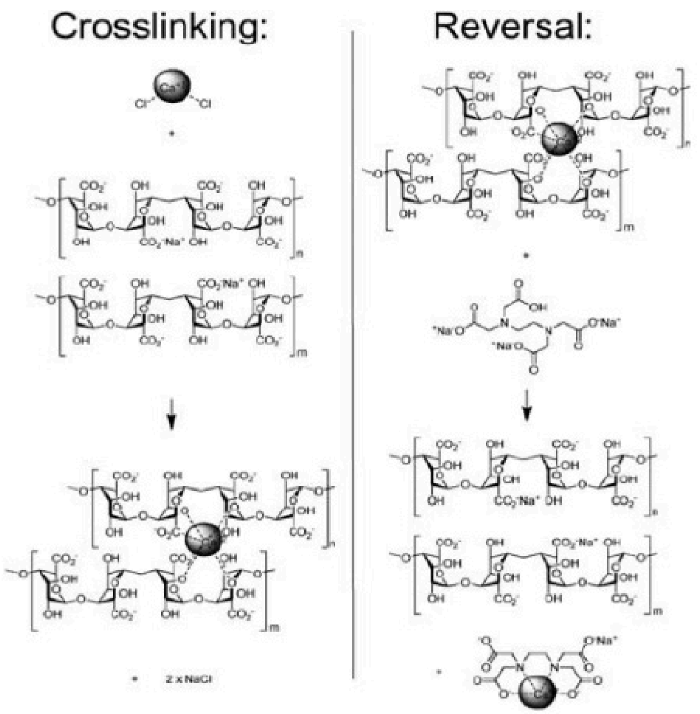
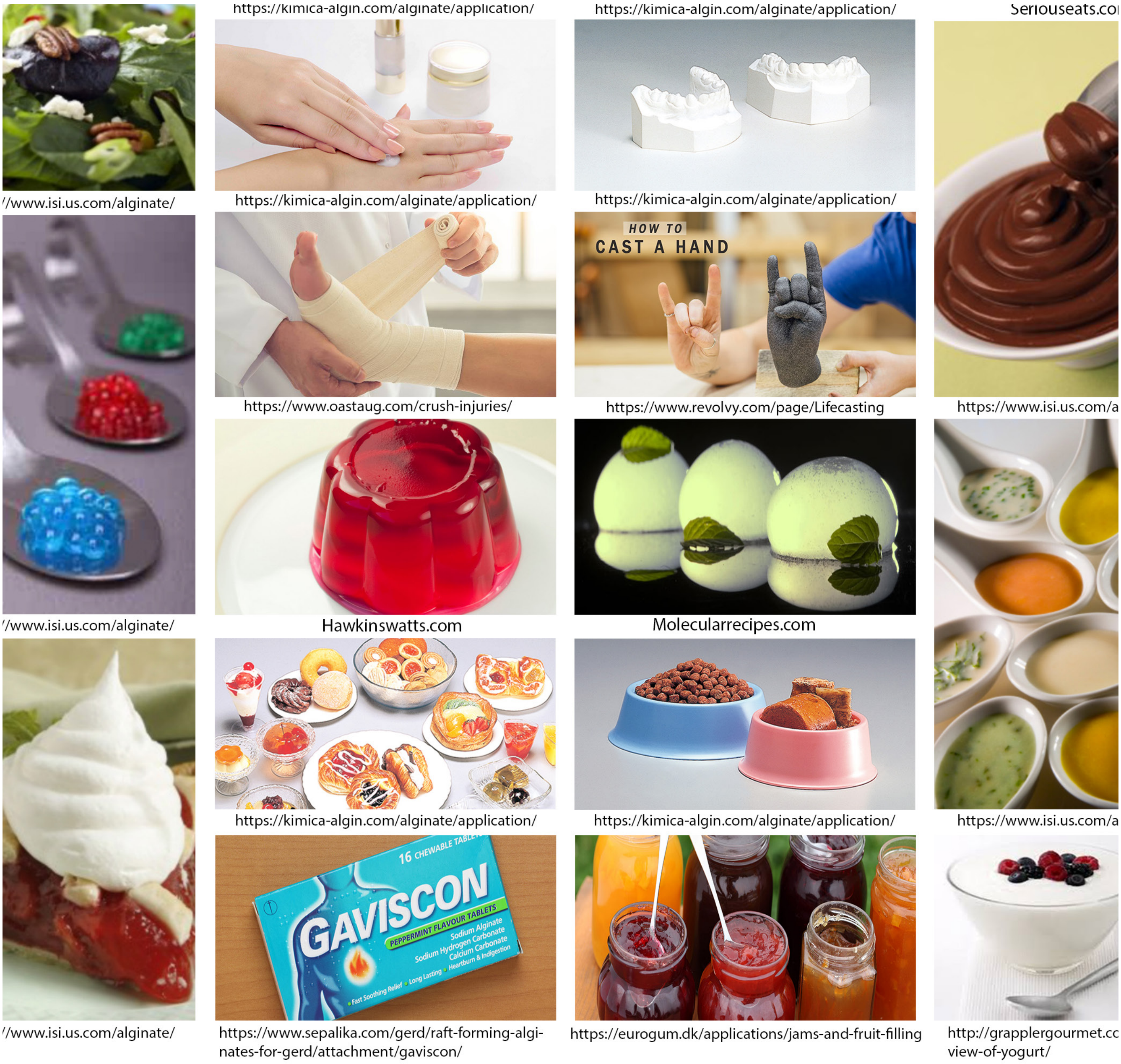


Figure 13: Detailed overview of crosslinking sodium alginate with calcium chloride and reversal. (Delaney, 2010)



https://kimica-algin.com/alginate/application/
https://kimica-algin.com/alginate/application/
Seriouseats.co

/www.isi.us.com/alginate/
https://kimica-algin.com/alginate/application/
https://kimica-algin.com/alginate/application/

https://www.oastaug.com/crush-injuries/
https://www.revolvy.com/page/Lifecasting
https://www.isi.us.com/a

/www.isi.us.com/alginate/
Hawkinswatts.com
Molecularrecipes.com

https://kimica-algin.com/alginate/application/
https://kimica-algin.com/alginate/application/
https://www.isi.us.com/a

/www.isi.us.com/alginate/
https://www.sepalika.com/gerd/raft-forming-alginates-for-gerd/attachment/gaviscon/
https://eurogum.dk/applications/jams-and-fruit-filling
http://grapplergourmet.cc
view-of-yogurt/

Fig. 14. Sodium alginate applications

Fig. 15. Cross-linking in gastronomy
(the organic solution)

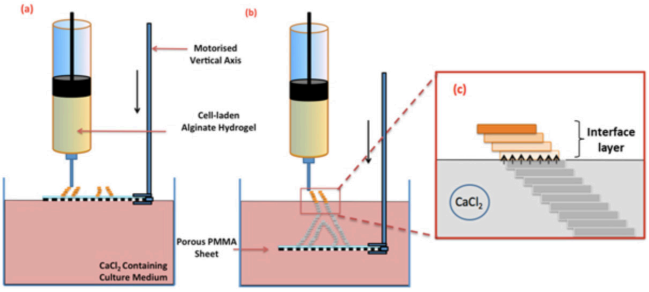


Fig. 16. 3D printing alginate & cross-linking (Tabriz et al., 2015)

2.4 Acceptance of sustainable materials

All that is previously mentioned forms the basis of the newly developed sustainable material; the mussel alginate paste. But is this new material going to be accepted when it is introduced to the public?

The way materials are aesthetically appreciated can be influenced by the (in)congruity between the visual and tactile properties of a material (Sauerwein et al., 2017). This means that, when introducing this unfamiliar material, the contrast between the 'look' and 'feel' can be used as possible design strategy because it might elicit positive surprise and finally appreciation (Sauerwein et al., 2017). Except for surprise, many other factors can influence the material acceptance. Therefore, in chapter 5, an experiential characterisation user research is carried out, using the Ma2E4 toolkit. When the experience of the material is known something about material acceptance can be said.

2.5 Discussion

The first point of discussion of chapter 2 is about sodium alginate, and whether or not it matches with a CE. As shown in figures 9 and 10, acids are used for the production of sodium alginate. Those acids are discarded, and can not be used again, which is against the principles of a circular economy. Despite the small amount of sodium alginate used in the paste (3%), it would be better to match this 3% with a CE as well. As explained in 2.3.2, a new alginate-like material called Kaumera is under development, which can be sourced from sewage (Verdonk, 2019). This material fits with a CE and can in the future (when it is sold) possibly replace the sodium alginate since it has (almost) the same properties as alginate. Therefore, testing and using Kaumera will be one of the recommendations for the future. Until then sodium alginate is used.

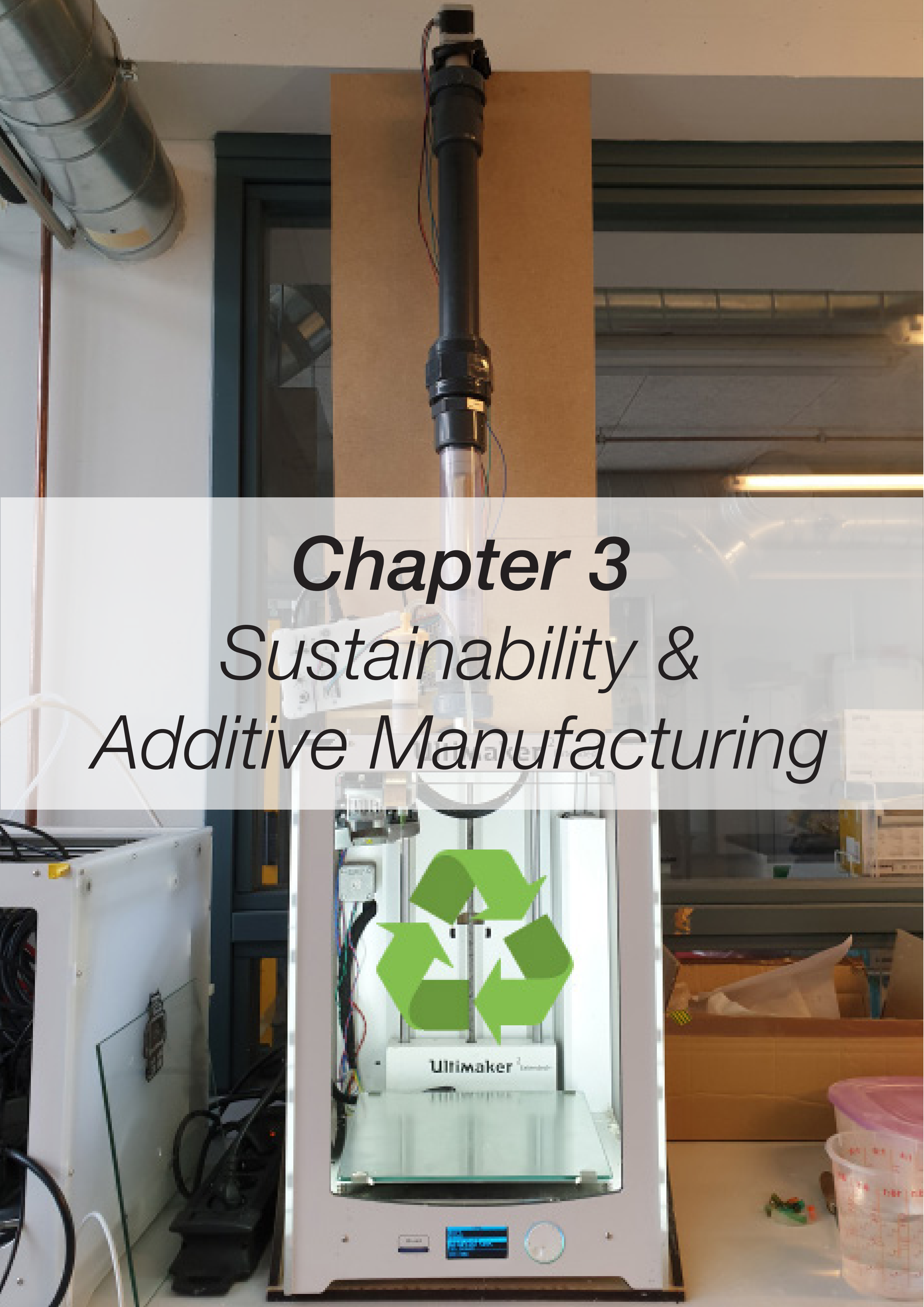
The second point of discussion is the crosslinking of sodium alginate. The reason why the crosslinking of calcium carbonate is negligible is already discussed. Tap water (in the Netherlands) however, contains calcium ions as well, and this tap water is used to create the paste. According to waternet (Waternet.nl), this is +/- 42 mg/L. Although this influence is bigger than the influence of calcium carbonate (0.1mg/L), it is still negligible. However, a very small amount of cross-links will be made. For that reason, demineralized or distilled water can be used instead.

2.6 Conclusion

From this chapter, multiple insights were derived. We already knew that mussel shells create a massive waste stream in the Netherlands, but because the 2 biggest mussel processing companies merged, the annual amount of waste in Zeeland will increase even further. Therefore Zeeland is chosen as the local manufacturing area. This knowledge will be important for decision making in future chapters. Furthermore, Delaney (Delaney, 2010) shows that calcium chloride can be used for crosslinking, and an EDTA solution can be used to reverse the crosslink. When prints will be crosslinked this is useful knowledge. Finally, sustainable material acceptance was discussed and it was concluded that more research has to be done on the acceptance and experience of this sustainable mussel alginate material, which will be done in chapter 5.

Chapter 3

Sustainability & Additive Manufacturing



3.1 Introduction to additive manufacturing

The AM technology used in this project looks most like Fused Deposition Modelling (FDM) and is based on material extrusion, see figure 17. The biggest difference between FDM and the setup used in this thesis is that the mussel paste does not have to be melted before printing, while FDM (usually) melts plastics. Appendix 2 gives an overview of other AM technologies.

Over the last couple of years, material extrusion proved to have the potential for a wide variety of applications. Material extrusion with plastics have been around for some time, but material extrusion with other materials has emerged at a rapid pace. In 2014, the Chinese company WinSun Decoration Design Engineering 3D printed 10 houses in Shanghai within a day for less than $5,000 each, using quick-dry cement (Goldin, 2014). In gastronomy 3D printed food is emergent (Godoi, 2016) because the layered structure contributes to the taste experience, for example when printing (vegetarian) steaks (Dick, 2019). In the pharmaceutical sector drug development using AM is upcoming (Trenfield, 2018) and in the biomedical world biobased material is being used to 3D print customized implants (Chen, 2017) and discover the possibilities for printing with human tissues (Chia, 2015) like organs, muscles, and bones (Bose, 2013). One of the most recent AM developments is 4D printing, a process through which a 3D printed object has the added dimensions of transformation over time, for example by using hydrogels as the active materials. A hydrogel is a 3D polymer network which can hold a large amount of water due to cross-linking. This technique is used for 'hydrogel thermal actuators' (Bakarich, 2015). However, most of these examples might be hard to use in combination with a circular economy, since materials are required to be sustainable and must have the possibility to be recycled. To be able to match AM with a CE, a look at the definition and strategies of a CE was given.

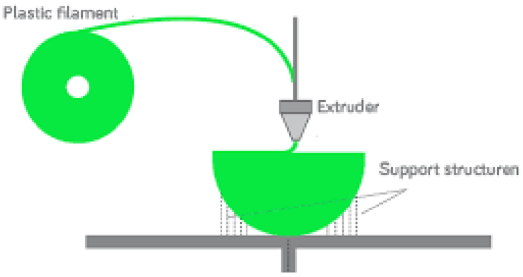


Fig. 17. Fused Deposition Modelling (FDM) (Deminifabriek)

3.2 Strategies for a Circular Economy

A Circular economy (CE) is an economic system aimed at eliminating waste and the continual use of resources (Bocken et al., 2016). As the Ellenmacarthur foundation describes it, is based on three principles: Designing out of waste and pollution materials, keeping products and materials in use, and regenerating natural systems. The concept of the circular economy is explained in figure 18 (MacArthur, 2013). These 3 principles from the Ellenmacarthur foundation can also be recognized in the 4 strategies described on https://www.circularstrategies.org: narrow loops, slow loops, close loops and regenerate loops, shown in figure 19. These 4 strategies will be used in chapter 6 to evaluate and create concepts.

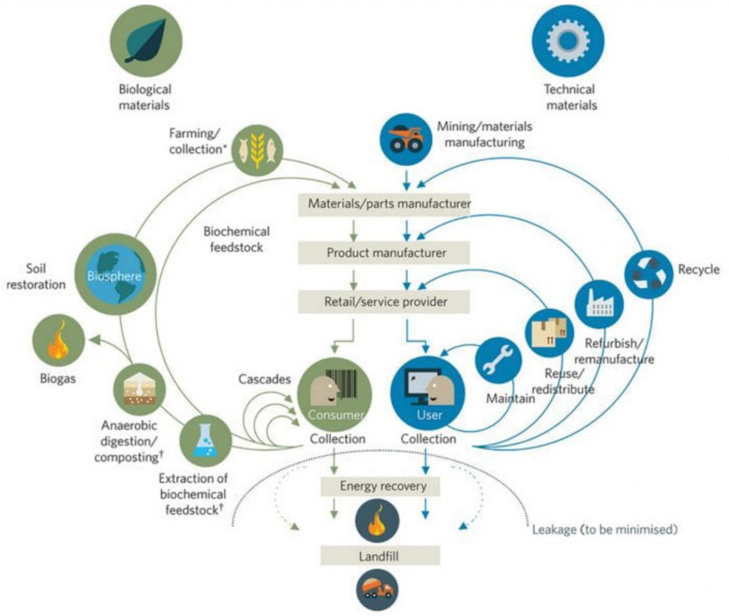


Figure 18: The Circular Economy explained (https://www.ellenmacarthurfoundation.org)

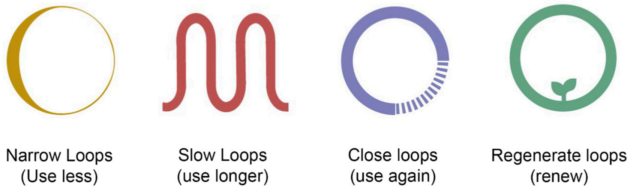


Fig. 19. Circular strategies (https://www.circularstrategies.org).

Narrowing loops means less energy, material, components, and products are used during the making and delivery of products or components. **Slowing loops** means products, components or materials are used longer over time. This can be done by making high-quality products and offering services, such as maintenance, spare parts or repair. **Close loops** means the recycling and re-use of waste products, components, and materials, and also the use of biodegradable materials (and their safe disposal). **Regenerate loops** means the decrease of hazardous substances, the increase of renewable energy, the regeneration of natural ecosystems.

With those strategies in mind, it will be easier to determine the value of the future concepts to the CE, and steps can be taken to match them with the CE even more.

3.3 Additive manufacturing for a circular economy

The potential of AM for sustainable production lies within the ability to use its digital and additive nature. This nature provides opportunities to save resources, for example, to repair products by creating spare parts (Matsumoto et al., 2016) or by avoiding material losses when you compare it to conventional techniques (Mani et al., 2014). Because AM is able to operate on a small scale and on-demand, it is seen as a suitable way of manufacturing for local production (Kohtala, 2015). Because local production reduces transportation significantly (compared to centralized production), it is seen as a sustainable substitute (Sauerwein, 2018).
Furthermore, local production enhances the recycling of local products (without it needing to be transported beforehand) and locally produced products might increase the user-product connection (Prendeville, 2016). However, the materials needed for AM can hardly be sourced locally and are therefore gathered from a centralized location (Sauerwein, 2018). While some companies are making progress in local recycling, the sourcing of local raw materials for AM is still a challenge. That is why previous research (Vette, 2018; Sauerwein, 2018) pointed out mussel shells as local and raw material for AM.

3.4 Applications

The advantages of AM are design freedom, faster product development, local production, on-demand manufacturing and low startup costs (van Wijk & van Wijk, 2015). It offers the possibility of a simple and low-cost supply chain. Locally produced materials can be used in your printer at home, which leaves out the need for mass production. Plastics (based on fossil fuels) have a big impact on the environment, which does not match the CE. Nowadays, plastics are being upcycled and 3D printed to tighten the circular economy loop (Zhong, 2018) or they can be made with biomass, of which some have unique characteristics when combined with AM (van Wijk & van Wijk, 2015). When combining 3D printing with the creation of these materials, innovative products arise. The possibility of 3D printing biobased materials is the way to go to succeed in a truly sustainable and circular economy. The MDD method (Karana et al., 2015) this project is based on, starts with benchmarking present materials containing similarities with the new developed material. In that way, you can find out if there are already partly similar projects going on. For that reason figure 20 shows benchmarks of 3D printed products that are manufactured nowadays using 1) 3D printed pastes and 2) 3D printed (natural) waste. These 2 material directions are relevant for this project since mussel-alginate fits within both benchmarks. For the benchmark projects made by 'material extrusion' are displayed, because they have most in common with this project. Figure 21 shows present and (possible) future applications for 3D printing in general, which (with some adaptations) might have the potential for a CE as well.

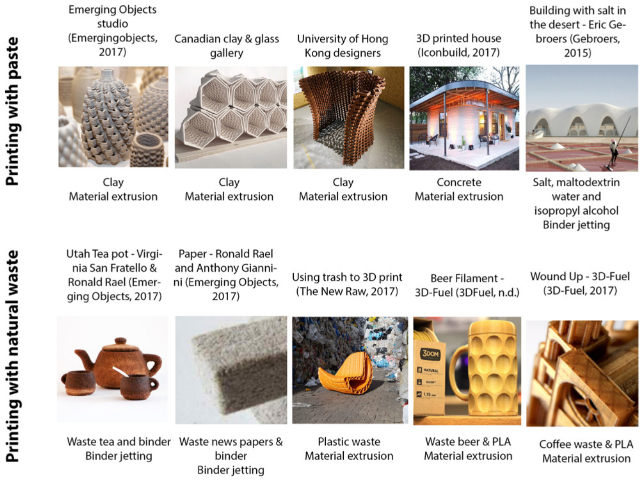
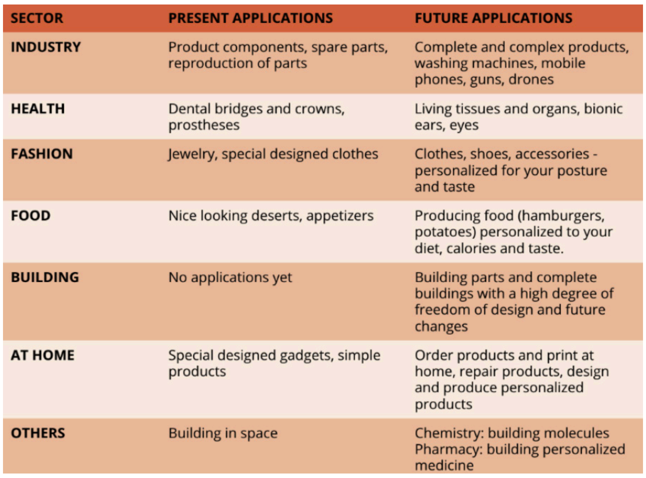


Fig. 20. Benchmark 3D printing



SECTOR	PRESENT APPLICATIONS	FUTURE APPLICATIONS
INDUSTRY	Product components, spare parts, reproduction of parts	Complete and complex products, washing machines, mobile phones, guns, drones
HEALTH	Dental bridges and crowns, prostheses	Living tissues and organs, bionic ears, eyes
FASHION	Jewelry, special designed clothes	Clothes, shoes, accessories - personalized for your posture and taste
FOOD	Nice looking deserts, appetizers	Producing food (hamburgers, potatoes) personalized to your diet, calories and taste.
BUILDING	No applications yet	Building parts and complete buildings with a high degree of freedom of design and future changes
AT HOME	Special designed gadgets, simple products	Order products and print at home, repair products, design and produce personalized products
OTHERS	Building in space	Chemistry: building molecules Pharmacy: building personalized medicine

Fig. 21. Present and future 3D printing applications (van Wijk & van Wijk, 2015).

3.5 Printer setup

The used printing setup in this project is shown in figure 22. Creating a print starts with turning on the control unit. This sends electrical waves to the stepper motor on top of the extruder, which starts to rotate a leadscrew. This leadscrew presses on the stoneflower piston inside the extruder which presses the piston of the syringe. Therefore paste is forced through the connecting tube which is connected using a luer-lock, which is a turning lock (figure 23). At the end of the tube, a nozzle is connected by using a luer-lock as well. When the paste exits the nozzle (which may take some time) the Ultimaker gets turned on and the print starts.

Fig. 22. Used printer setup

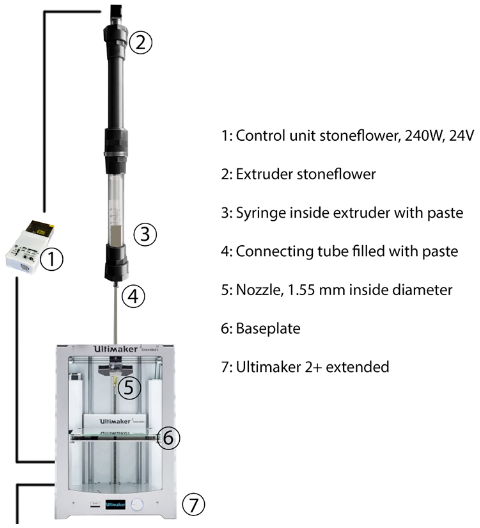


Fig. 23. Luer-lock

3D printing in Zeeland

Vette (Vette, 2018) described that the printer setup shown above is an accessible setup, and therefore does not have to be difficult to set it up on different locations in Zeeland. When he used his setup for local production in Zeeland, he researched both 3D printing companies and individuals that can be approached for collaboration. Therefore he used the 3D Printing Atlas, created by the Kamer van Koophandel (2016) and the biggest registration of individual 3D printer users at 3D hubs.com. Based on this he concluded there were enough collaboration possibilities (in 2018). By using his method for this project (in 2019), there can be concluded that the amount of individual 3D printers and 3D print companies grew, meaning there is even more space for collaboration. The registered amount of 3D printer users in Zeeland on 3D hubs.com increased from over 20 (Vette, 2018) to 33 (3DHubs.com) in one year. Figure 24 shows the increase of 3D printing companies in the area of Yerseke, from 7 in 2018 (Vette, 2018) to 9 in 2019 (3D printing atlas, 2019).

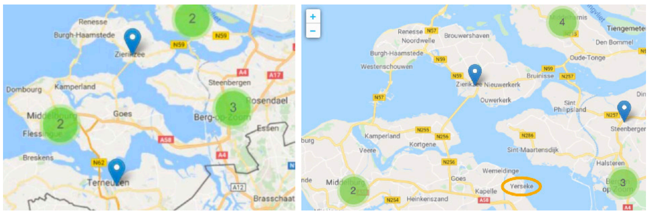


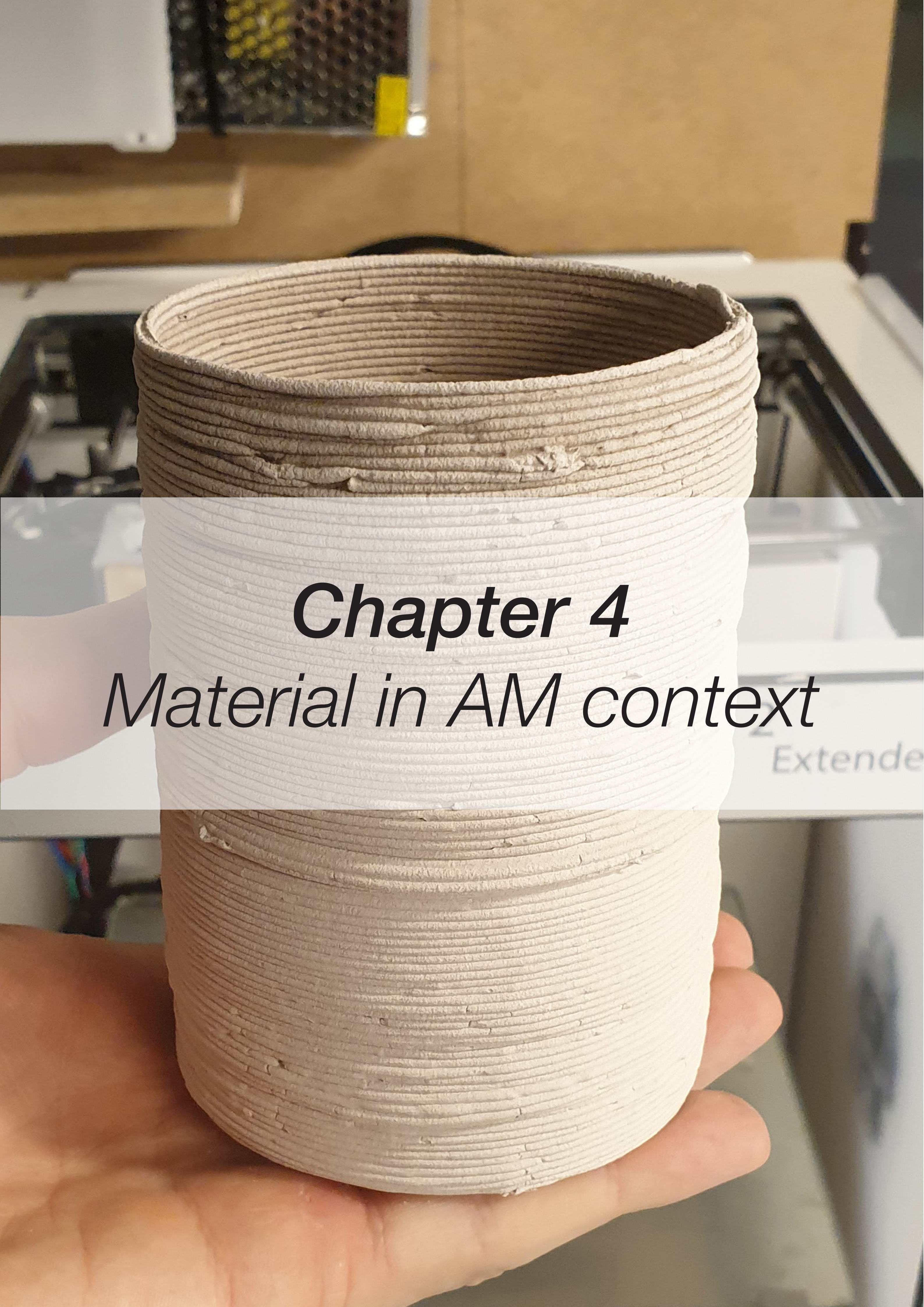
Fig. 24. Registered AM companies close to Yerseke in 2018 (left, Vette, 2018) and 2019 (right, 3D printing atlas, 2019)

3.6 Conclusion

This chapter explained 4 strategies that will be used to evaluate and create concepts for a CE in chapter 6. Furthermore, the benchmark shows that there is a large public interest in 3D printing with biobased materials, natural waste and pastes similar to mussel-alginate. Subsequently, it appeared there are even more possibilities for collaborations with 3D printer users and companies in Zeeland than previously researched (Vette, 2018). In the next chapter, we examine if the printing setup (figure 22) is suitable for the goal of this project, and the first step in optimizing the paste will be carried out. Since this chapter ends the literature phase, Appendix 4 gives a brief overview of the most important literature used thus far.

Chapter 4

Material in AM context



4.1 Introduction material in AM context

The goal of this thesis is to find a suitable application for the mussel-alginate paste. Since there is an already existing mussel-alginate paste, it gives us a starting point and therefore the iterative process starts at ‘Material in AM context’. Part 4.2 shows how the current paste is made. After getting acquainted with this material, and creating a feel for the process, product possibilities can be estimated. This chapter is based on ‘tinkering with the material’ from the MDD method, which is an explorative process to get to know the qualities and constraints of the material.

4.2 Creating the mussel-alginate paste

The already existing material was made by Sauerwein (Sauerwein et al., 2018) and Vette (Vette, 2018). Their process started with cooking the mussel shells to get rid of everything other than the shell. By heating the shells in an oven for an hour at 200 °C, they were brittle enough to grind them with a HERZOH disk mill. Finally, a sieving machine filtered out the small particles, in this case, particles smaller than 75 microns. The research in this thesis uses the same particle size since the process stays the same and this particle size created a printable paste (Vette, 2018).

During some experiments with the mussel-alginate material, the starting point material composition was: 3% alginate, 40% water & 57% mussel. Creating the paste (figure 25) starts by measuring 40% (mass percentage) water using a scale. The second step is adding 3% alginate in well-stirred water. This order made it more easy to mix the alginate with the water, probably because the alginate chunks do not stick that much to the beaker walls, although there is no literature to support this hypothesis. By stirring the water first, solubility is increased. Stirring is required until a homogeneous gel arises; then the binder of the paste is finished. The last step in creating the paste is to add the filler. The pulverized mussel shells contain approximately 95%-99% calcium carbonate (Barros et al., 2008). Adding this filler creates a heterogeneous paste, since the binder stays between the calcium carbonate molecules, instead of dissolving. Since it does not dissolve, there is no reversible crosslinking between the alginate and the calcium carbonate. This has the benefit that it can be recycled by mixing it solely with water, but has the disadvantage that the extra strength cross-linking can create is unused. The figure below shows the process of making the paste.

1: calibrating the scale
2: put the beaker on a scale and reset weight to ‘0’
3: drip water in the beaker
4: add sodium alginate to the water
5: mix till a homogeneous gel is created
6: add mussel-shell powder
7: paste is grainy when mixing
8: after some time a smooth paste is created
9: fill the syringe with paste
10: put the piston and stopper in the syringe

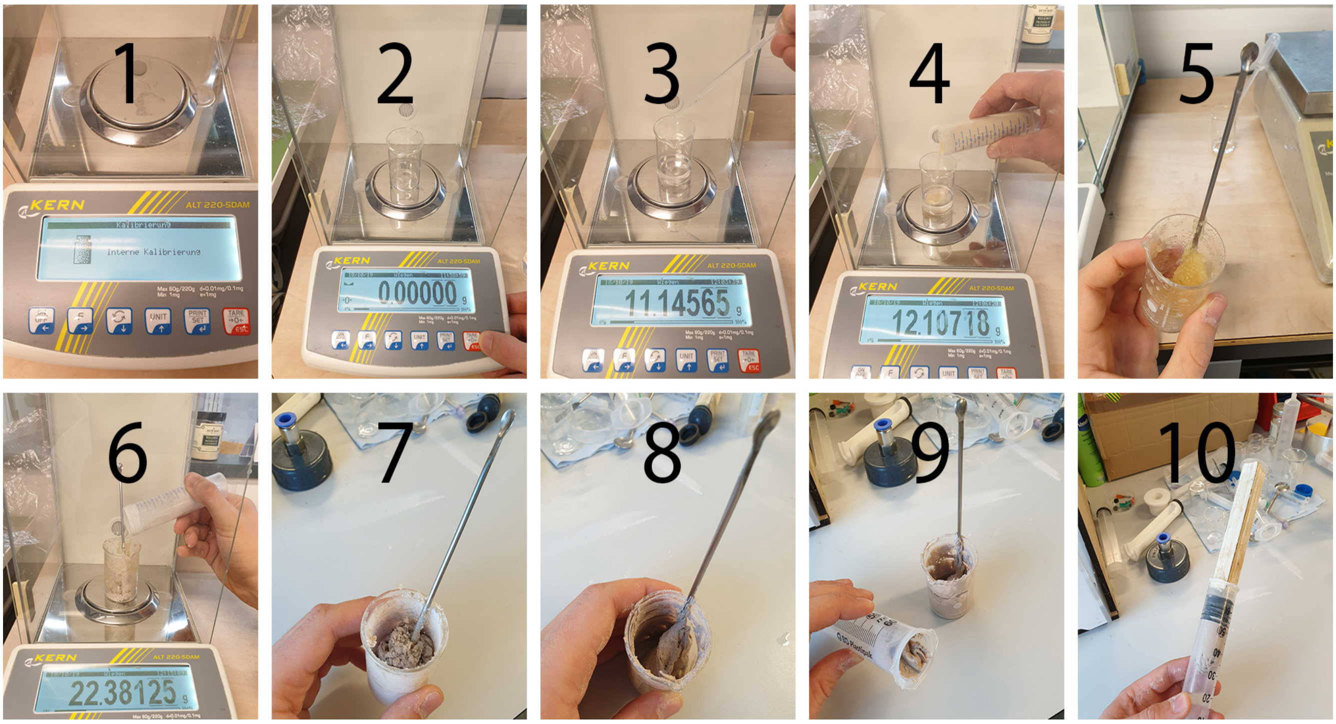


Fig. 25. Paste preparing process

Fig. 26. Material blowout

Fig. 27. Collapsed star

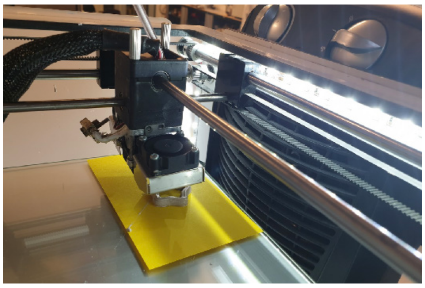


Fig. 28. Setup speeded drying test

The last two steps have to be executed with care. When air remains in the syringe when filling it, this air will get under high pressure. The piece of paste in front of the air bubble will get blown out of the nozzle by the pressure. Figure 26 shows a material blowout (left side).

4.3 Improving print stability by fast drying

In the case the final application becomes a product, the paste has to be able to make tall prints without collapsing. Since it is a paste, it hardens by drying (evaporation of water), in contrast to (for example) plastics, which hardens by solidifying (phase transition). Therefore, the necessary drying time is expected to be higher. This means the foundation for 3D printing may be weaker (Malaeb, 2015). A first test has been executed to find out if it is possible to make tall prints with the current material. For the first tests, the simple form of a star-shaped tube is used. Figure 27 shows the result of the first attempt to make a tall print with mussel-alginate paste. Halfway through the printing process, the foundation underneath turned out not to be strong enough to hold the weight, and started to deform; the walls slowly started to collapse inwards. Because of this deformation, the new material could not be placed properly on top of the previous layer. To improve the printing stability of the paste a speeded-drying test was carried out. By creating a foundation of (partly) dried paste, the deformation might be less significant in such a way that higher prints might be possible. Four situations were tested; (1) without speeded drying, (2) speeded drying with fans at room temperature (20°C), (3) speeded drying with fans blowing air of 50°C and (4) speeded drying with a build plate temperature of 80°C. For this test an external fan was used, one with the possibility to create a heated air stream as well. Figure 28 shows the setup for this test. By using the same star-shaped model and printer settings, the impact of speeded drying could be tested.

Figure 29 shows the results of these four situations. As a reference, the first situation (first test) shows what happens without speeded drying. The first situation uses solely the fan of the Ultimaker itself. This Ultimaker fan, however, is designed for printing with plastics. Test 1 shows the fan of the Ultimaker itself does not have enough influence for printing with a paste. The added external fan for test 2 at room temperature (20 degrees celsius) shows some improvement compared to situation 1. The figure shows that the side the fan was pointed at (left) encountered less deformation during printing than the other side (right). Test 3 (external fan on 50°C) shows a lowered deformation on both sides and was, therefore, able to make a taller print. Test 4 (base plate at 80°C) showed to be a slightly better improvement over test 3, as a higher print was established. The heat generated by the baseplate (test 4) forced the first layers to dry almost immediately because of the direct energy transfer (compared to the fan). Test 4, however, shows that the baseplate heat has little influence on upper layers, which are still deforming. To speed up the drying process of the upper layers as well, the base plate heat and the fan heat will be combined for future prints.

The fan heat used in the test did not increase the number of cracks in the dried material, but the hot baseplate did cause some cracks. There was no dried material in the nozzle (because of the speeded drying) that blocked the material flow (as was previously expected). Disadvantages of the material seemed to be that no sharp angles are possible to make a sharp shape, since the material is too fluid, which has to be taken into account in the design phase. The material also needs a lot of time to dry properly, cracking a print after 24 hours showed it had not yet properly hardened (figure 30).

Fig. 29. Speeded drying tests

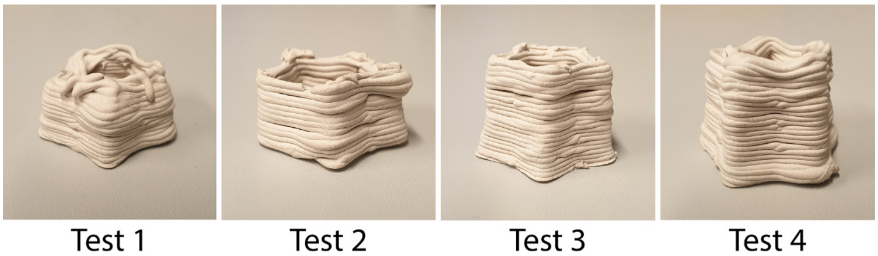


Fig. 30. Long drying time

Fig. 31. Printing on a post-it

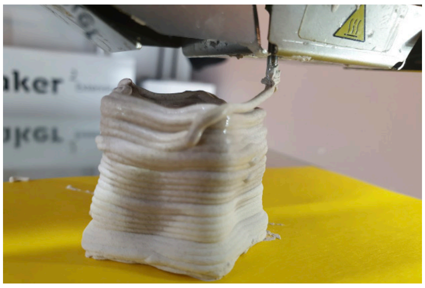


Fig. 32. Shrinkage cauzes floating nozzle

The test also showed some disadvantages for speeded drying as well. Baseplate adhesion is lost when speeded drying from a heated base plate takes place, resulting in a shifting object during printing, causing a printing failure at the beginning of the printing process. For that reason, prints will be made on a post-it when a hot baseplate is used since the material attaches to paper making it impossible to move during the process, see figure 31. This flat piece of paper has the benefit it sticks to the baseplate on its own. For larger prints bigger pieces of paper have to be used, but they have to stick to the baseplate.

4.4 shrinkage

A more significant problem, however, was that speeded drying means speeded shrinkage as well, resulting in a nozzle which at some point loses connection to the print. This will finally have the same result as the prints without speeded drying; upper layers miss connection and collapse (figure 32). Because of this shrinkage problem, the making of tall prints will still be impossible. Since the print quality is increased with speeded drying (figure 29), a possible solution for the shrinkage problem had to be found. In figure 33 the speeded drying results are displayed.

Fig. 33. Results speeded drying test

Insight 1	Ultimaker fan does not have enough influence for printing with a paste.
Insight 2	External heat fan had a positive effect on paste stability.
Insight 3	80°C baseplate had a small positive effect on height; no effect on upper layers.
Insight 4	The hot baseplate did create more cracks at the bottom layers.
Insight 5	Speeding the drying process did not cause dried material in the nozzle.
Insight 6	No sharp angles can be created with the material.
Insight 7	Material needs a lot of time to dry.
Insight 8	Baseplate adhesion is lost when baseplate temperature is too high.

When consulting literature about this matter a frequently used solution is to lower the amount of water, so shrinkage will be less of a problem and prints become more stable. Since there is no literature about printing mussel-alginate paste, possible solutions might be found in 3D printing with concrete or clay (Malaeb, 2015; van Herpt, 2018), which can be seen as pastes with drying time as well. Malaeb (2015) states that flowability of the paste (concrete) and the ability to hold itself and subsequent layers can be seen as opposites; the paste is liquid enough to print but collapses during printing, or the paste is viscous enough to give stability but is too viscous to print at all. Therefore, they performed executive testing to find the maximum viscosity which is still possible to work with. Based on the expertise of this company, it was decided to have a closer look at our own material composition, and test printing with less water. The first test was done with a 3% alginate, 35% water and 62% mussel composition. Printing with less water, however, resulted in buckling of the piston (figure 34a) and paste passing the piston head (figure 34b). The piston and rubber stopper were not designed for the amount of pressure created by the increased viscosity. Therefore a stronger 3D printed piston was used, which broke as well (figure 34c). Finally, the original piston was reinforced with wood and epoxy and the rubber stopper replaced by a bigger one that is able to endure more pressure (figure 34d).

Fig. 34a,b,c,d. System can not print the viscous paste

Even after these improvements, the pressure was too high for the rubber stopper, since paste was again pressed into the wrong direction, and even the syringe deformed a bit. This was a clear sign the current system could not handle the pressure caused by a more viscous paste. For this problem, the expertise of others was consulted again, which brought insights of an artist 3D printing with clay. The artist Olivier van Herpt (van Herpt, 2018) addresses the shrinkage problem and collapse problem as well. One of his breakthroughs came when he stopped mixing clay with water. By making his whole printer setup much stronger he was able to use hard clay, which solved the shrinkage problem and enabled him to print larger objects. Steel cables and an extruder able to press 60kN of pressure (figure 35), however, seemed not feasible in this project. This machine, however, made me realise that when the machine can not be strengthened as van Herpt did, and the paste viscosity has to increase, that somewhere in the printing setup the resistance has to be decreased. The old printing setup (used by Vette in 2018) suddenly came to mind (figure 36).

4.5 New printing setup

The printing setup used by Vette had one big advantage; the syringe filled with paste was mounted directly on the nozzle, so the pressure in the system was almost entirely dependent on the paste which had to be pressed through the nozzle. With the current system (figure 39, left) the path of resistance is way longer since it needs to flow through a connecting tube between the nozzle and the syringe filled with paste. The reason why the current system is used is because of the direct extrusion control; the current system uses a ram extruder (StoneFlower) and the old system uses air pressure which has delays and is more difficult to control. For a new printing setup, the 2 advantages of both systems (Vette, 2018) and insights about printing concrete (Hager, 2016; Malaeb, 2015) and clay (van Herpt, 2019) were combined, as shown in figure 37 & 39. Just as in the current setup, the ram extruder is used, but instead of forcing paste through the connecting tube, this system uses water. In that way, resistance in the system is decreased and (since water can not be compressed) there still is direct and easy control. In the second syringe, the pressure from the water is transferred to the paste with a small piston (used by Vette, Vette, 2018) and rubber stopper. It can be compared with a hydraulic system which is added, see figure 38. For such a system the pressure (P) stays the same at both ends. Since P=F/A this means the force (F) divided by the surface of the rubber stopper (A) is similar at both ends (F/A=F/A). Since the surface of the rubber stopper in the second syringe is smaller than in the first syringe this means that the force in the second syringe is smaller than the first one as well. This relatively low force on the paste in the 2nd syringe will probably not form a problem since the extruder is strong enough to extrude the paste anyway, but this has to be taken into account. What will make a difference, however, is that the difference in rubber stopper size also makes a difference in extrusion speed; the second rubber stopper moves faster than the first one. To keep the old extrusion speed the same with the old setup the 'extrusion speed setting' on the control unit has to be decreased a bit.

This new system solves the problem of the high resistance of the system when printing with a viscous paste. It has the added advantage that cleaning time is significantly decreased (since there is no paste in the connecting tube anymore). Therefore less material has to be thrown away in the cleaning process, which fits better with the requirements of a circular economy.

Fig. 35. Printer setup used by van Herpt (van Herpt, 2019)

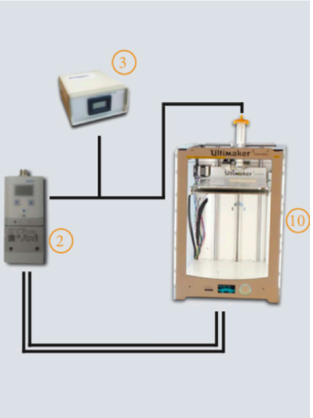


Figure 36: Schematic printer setup used by Vette (Vette, 2018)

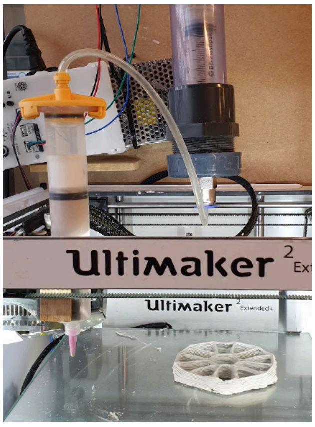


Fig. 37. New printing setup

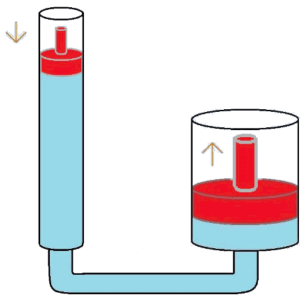
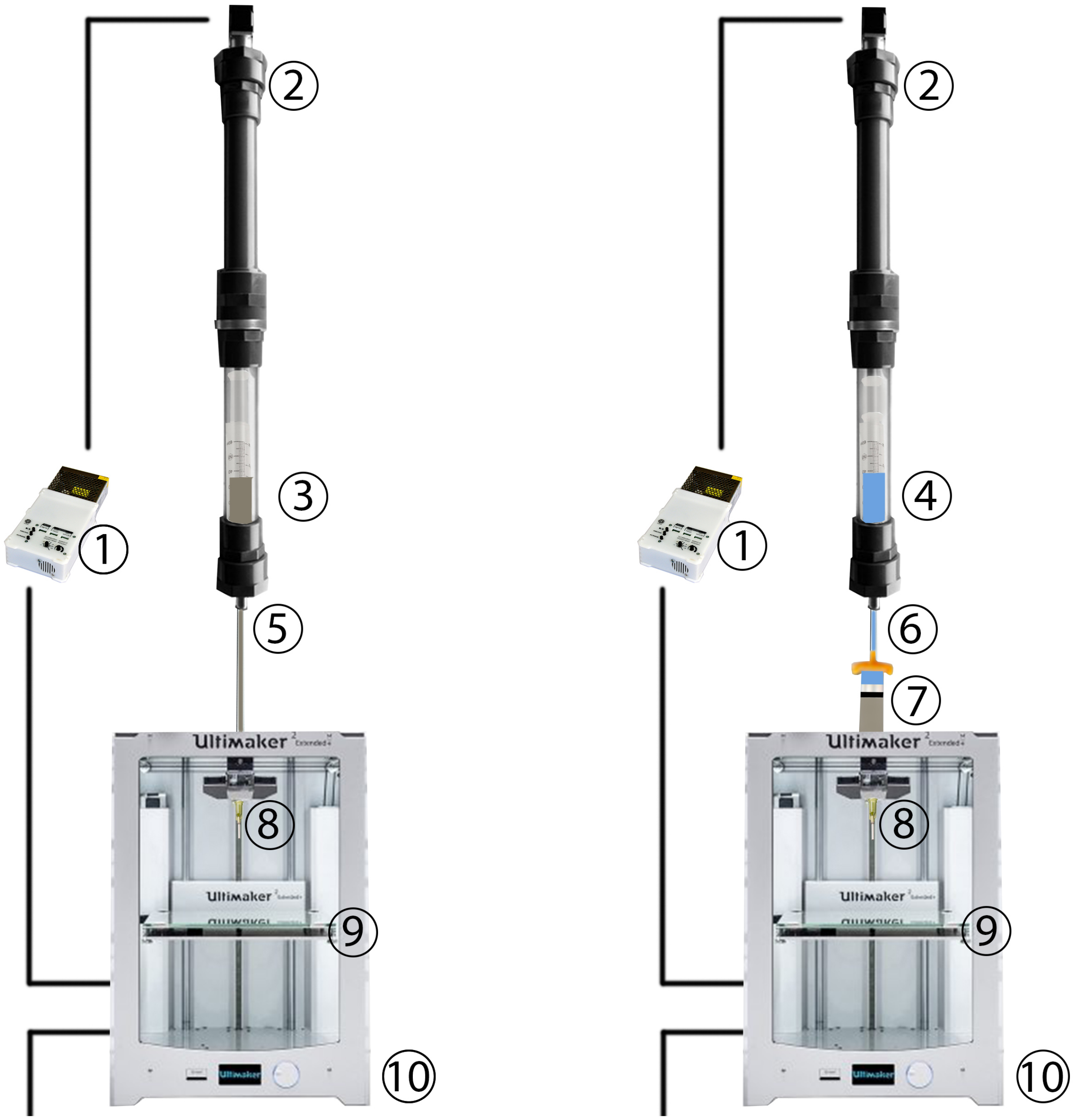


Fig. 38. Visual of an hydraulic system (cleanpng.com)



Sources the new setup is inspired on:

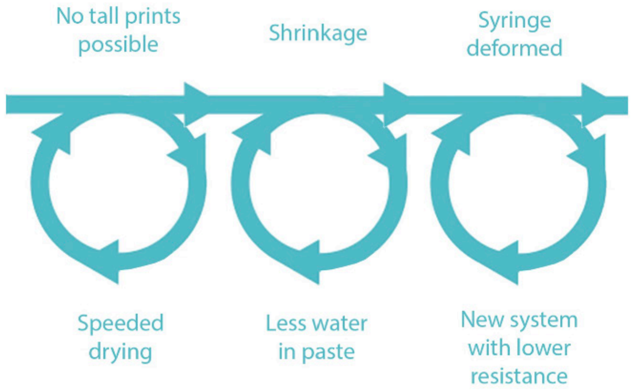
-Insights 3D printing clay (van Herpt, 2019)
-Insights 3D printing concrete (Hager, 2016; Malaeb, 2015)
-Advantage setup used by Vette (Vette, 2018)
-Advantage setup used by Sauerwein

Fig. 39. Current setup (left) and new setup (right)

1: Control unit Stoneflower, 240W, 24V, controls extruder
2: Extruder Stoneflower, pushes paste through the syringe
3: Syringe inside extruder filled with paste
4: Syringe inside extruder filled with water
5: Connecting tube filled with paste
6: Connecting tube filled with water
7: Water forces paste through the syringe
8: Nozzle, 1.55 mm inside diameter
9: Baseplate
10: Ultimaker 2+ extended

The black lines in figure 39 are connecting wires. The Ultimaker is connected to the power network (240V). The control unit is connected to the extruder, but also to the Ultimaker in case it is necessary to let the Ultimaker control the extrusion speed for a certain design. A side note is that retracting material is not going to work because the delay in the system is still too big for that. This has to be taken into account when designing the application. The most important iterations from this chapter are shown in figure 40.

Fig. 40. Overview of the iterative process

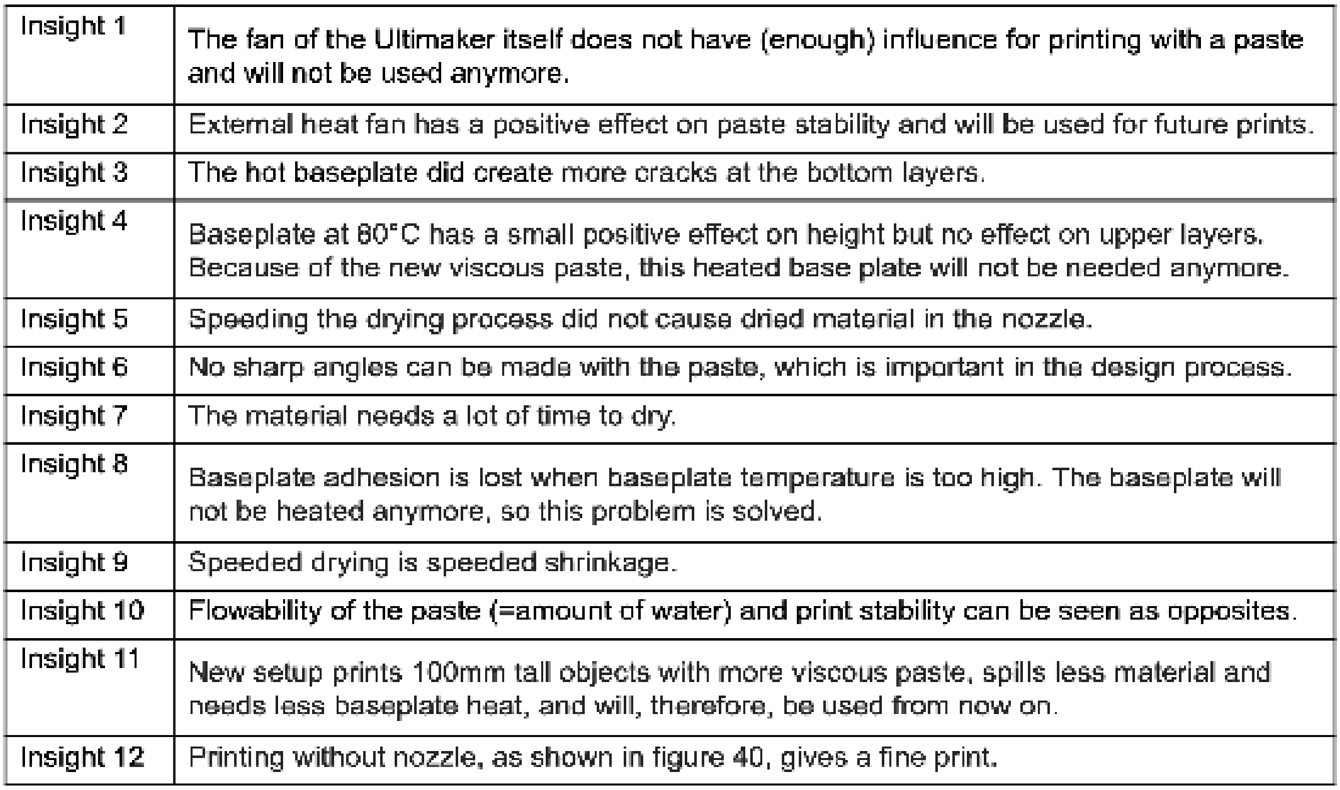


4.6 Conclusion

'Material in AM context' was an iterative process between changing the material, settings and the printer setup. Figure 41 gives an overview of all the insights from this chapter. In the end, the printing setup has been changed, which is now able to print with a more viscous paste. This system was able to print a 100mm tall object with 27% water, 3% alginate and 70% mussel shells, shown in figure 42. This figure also shows that printing without nozzle gives no problems. Since (to a certain extent) less water means less shrinkage and higher print stability (Malaeb, 2015; van Herpt, 2019), this system will be used from now on. The higher stability has the added advantage that baseplate temperature can decrease. Therefore less energy is used, which is a better fit with a CE.

Fig. 42. 100mm tall object printed with new setup

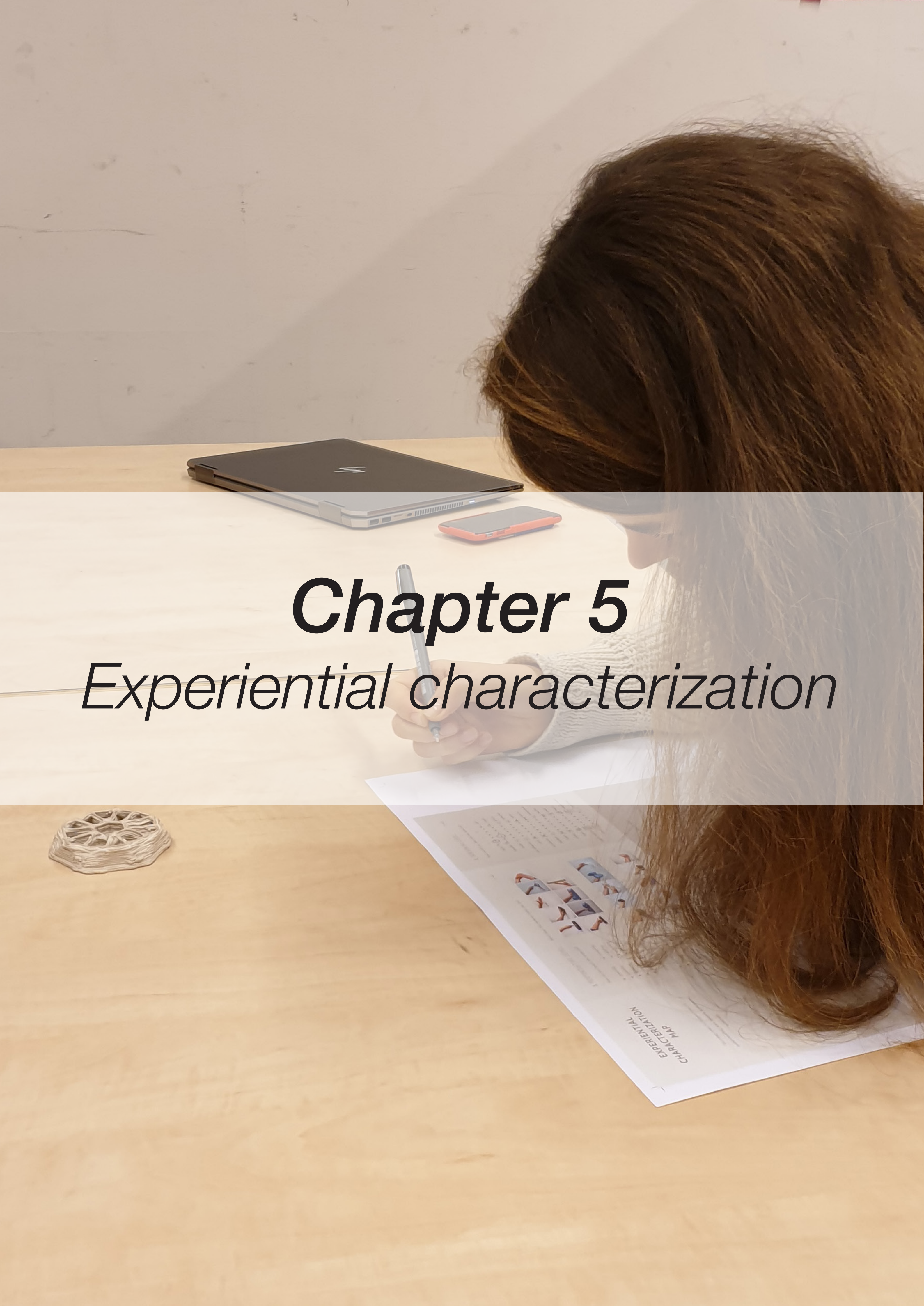
Fig. 41. Insights from chapter 4



Insight 1	The fan of the Ultimaker itself does not have (enough) influence for printing with a paste and will not be used anymore.
Insight 2	External heat fan has a positive effect on paste stability and will be used for future prints.
Insight 3	The hot baseplate did create more cracks at the bottom layers.
Insight 4	Baseplate at 80°C has a small positive effect on height but no effect on upper layers. Because of the new viscous paste, this heated base plate will not be needed anymore.
Insight 5	Speeding the drying process did not cause dried material in the nozzle.
Insight 6	No sharp angles can be made with the paste, which is important in the design process.
Insight 7	The material needs a lot of time to dry.
Insight 8	Baseplate adhesion is lost when baseplate temperature is too high. The baseplate will not be heated anymore, so this problem is solved.
Insight 9	Speeded drying is speeded shrinkage.
Insight 10	Flowability of the paste (=amount of water) and print stability can be seen as opposites.
Insight 11	New setup prints 100mm tall objects with more viscous paste, spills less material and needs less baseplate heat, and will, therefore, be used from now on.
Insight 12	Printing without nozzle, as shown in figure 40, gives a fine print.

Chapter 5

Experiential characterization



5.1 Introduction

‘Materials’ of product designs have been a fundamental point of interest in research for several years (Ashby & Johnson, 2009). Most researchers are focussed on providing designers with a tool to choose the right material for their designs (Ljungberg, 2010; Ashby & Cebon, 2007). Others mainly focus on how we sense materials in products (Rognoli, 2010; Hurcombe, 2007), how we add meanings to materials (Karana et al., 2009; Karana 2010), and how materials in products evoke emotions (Ludden et al., 2008). However, how to design for experiences with a certain material at hand has only recently been described in the Material Driven Design method (MDD). This method states that the experience of a material is ‘not only for what it is, but also for what it does, what it expresses to us, what it elicits from us, and what it makes us do’ (Karana, Barati, Rognoli, & Zeeuw van der Laan, 2015). To cover both the functional and experiential parts of material design, the MDD includes both a technical and experiential characterisation. This chapter focuses on the experiential characterisation of the developed material.

5.2 Material Experience

The MDD method focuses on 4 different levels of materials experience in product design (see figure 43). These four levels are described below:

Performative: the first level is about what we perform with the material, our actions. How does the material gets touched, moved or hold? For example, a material that gets experienced weak (sensorial), disgusting (affective) and strange (interpretive) will get handled differently than a strong (sensorial), loved (affective) and professional (interpretive) product.

Sensorial: In the second stage, the technical properties of the material are experienced with your senses by touch, vision, smell, (sound and taste). Examples are hardness, smoothness, weight, etc.

Affective: after your senses are used, emotions will arise due to what you discovered; the second level is about the emotions the material elicits. Examples are disappointment, attraction or comfort.

Interpretive: The fourth level is about how the material gets interpreted and judged. What meanings do we give the material after the initial sensorial encounter? Examples are modern/traditional or aggressive/calm.

To get a full understanding of the material experience of the mussel-alginate material, the material experience on all four levels was tested.

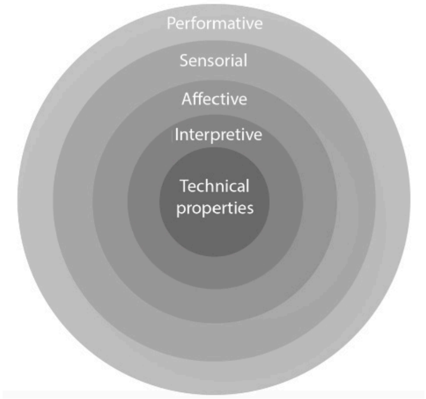


Fig. 43. Four levels of material experience (Karana et al., 2015)

Method

To determine the material experience on all four levels the Ma2E4 Toolkit, developed by Karana and Camere (n.d.) is used. This Toolkit aims to support in understanding how people experience materials. The Toolkit provides vocabulary and structure to seek an answer to how the material is experienced. The toolkit is used in a setting were the designer acts as the facilitator and asks questions to the participant about a specific material. A 5-step experiential characterization map is used as guidance. Those 5 different steps (four levels+final questions) will be explained further with the results. The final goal of this user test is to end up with a comprehensive understanding of the material experience of the mussel-alginate paste which can serve as a starting point for the ideation phase. The characterisation maps are displayed in appendix 5.

Setup

This user research has a one to one setup, with the designer as facilitator asking questions to the participant. This test is performed in a silent and private room at the faculty of IDE. The private room (reserved at the service desk) makes sure no unintended influences from the outside (noise, movement, etc.) have an impact on the results. The room has plenty of natural light (in addition to artificial light) to make sure every detail of the material can be seen. To keep all the parameters as steady as possible, all the user tests will be done in the same room with the same amount of daylight, using the same test structure. During the test, notes will be taken of every action and question coming from the participant. Figure 45 shows the used test setup.

Ma2E$_4$

Fig. 44. Toolkit (Karana et al., 2015)

Fig. 45. Setup experiential characterization test

Participants

To give the conclusion of this user test some value, the sample size was decided to be 20. Although this is considered to be a small sample size (=N<30, Wikibooks), it will be enough to get an idea about the material experience. Among the 20 participants, there were 10 men and 10 women, as shown in figure 46. Furthermore, the sample was a mix between students (16x) and non-students (4x), young participants (17x) and older participants (3x) and IDE students (13x) and other studies (3x).

Participant	***Male/Female***	***Age***	***Student/non-student***	***Study***
Participant 1	Female	25	student	Brain Sciences
Participant 2	Female	55	non-student	-
Participant 3	Female	28	non-student	-
Participant 4	Female	60	non-student	-
Participant 5	Male	57	non-student	-
Participant 6	Male	24	student	Industrial Design
Participant 7	Male	24	student	Industrial Design
Participant 8	Female	20	student	Architecture
Participant 9	Female	21	student	Economics
Participant 10	Male	25	student	Industrial Design
Participant 11	Male	25	student	Industrial Design
Participant 12	Male	24	student	Industrial Design
Participant 13	Male	23	student	Industrial Design
Participant 14	Male	23	student	Industrial Design
Participant 15	Male	20	student	Industrial Design
Participant 16	Female	22	student	Industrial Design
Participant 17	Male	25	student	Industrial Design
Participant 18	Female	24	student	Industrial Design
Participant 19	Female	25	student	Industrial Design
Participant 20	Female	25	student	Industrial Design

Fig. 46. Participants user test

Shape

The shape of the provided material sample is of importance since it influences the experience. When it is designed in the form of a vase, associations with ceramics (porcelain, clay, etc) might arise. Therefore a sample based on the design of Joost Vette (Vette, 2018), is used (see figure 47 & 48). This design was created because it is unlikely it will implicate a function and therefore influence the experience. Furthermore, it was important to show the freedom of shape enabled by its additive manufacturing. AM was preferred over casting since the layers contribute to the experience (Vette, 2018).

Fig. 47. Neo-alginate sample by Vette (Vette, 2018)

Fig. 48. Sodium-alginate sample

Most important with recreating this sample is the minimum wall thickness of 1.55 mm. The used nozzle is 1.55 mm, so any thinner walls will give errors in the Cura slicing software. To decrease the chance of collapsing, the design was printed upside down (see figure 49).

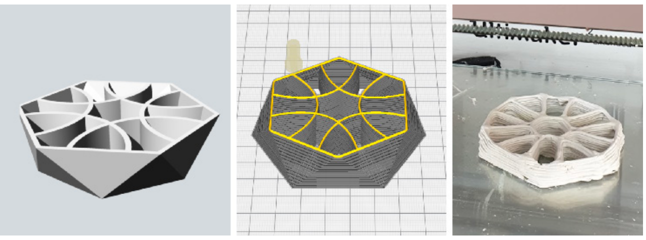


Fig. 49. Printing the sample upside down to decrease the chance of collapsing.

5.3 Test results

The user test contained 5 steps, which will be discussed below in the order of the method. Every step will start with the actions taken after which the results will be discussed.

Performative material qualities

The participant was given the sample and was asked to freely explore the material. That is all the information they were given at this point. The facilitator kept a close eye on every action performed and documents this using the map. In order to stimulate the participant to explore the material further, a question is asked after some time; *"Describe what the material makes you do?"* To elaborate on this question three sub-questions were asked: *"How do you touch the material?", "How do you move the material?"* and *"How do you hold the material"?* These questions triggered the participants to think about the different ways to touch, hold and move the material. Figure 50 shows the actions taken by the participant, and the number of times (=n) they were done.

The first action most of the participants performed was rubbing the sample because they noticed it was 3D printed and wanted to find out how this felt (all participants declared, in the end, they knew it was 3D printed). Pressing, caressing and turning the material to watch all sides were other ways they used to discover the texture. 12 of the participants tapped the material on the table, to hear what sound it made. What they heard was for most of them different than what they expected. *"it has the looks and feel of ceramic, but the sound and weight of plastic"* is what subject 14 said. The touch of the material was not liked by everyone (1,6,10), but others mentioned it as a positive feel (4,5,7,11,16,17,18). One of the participants said, *"It looks hard and cold but feels warm and soft"* (17). Just two participants smelled the object, but they could not smell anything. Since the object was totally dry and 1 week old, the ocean-smell was almost entirely worn off. Compressing, scratching and pushing was used to test the properties of the material since they wanted to know how strong it was. 7 of the participants bent the material, after which a few (8, 11, 16) asked: *"how bad is it if I break it?"* About a quarter of the participants weighed and lifted the sample, which elicited reactions about its low weight: *"it is lighter than it looks"* was mentioned spontaneously by multiple participants (2,3,5,6,11,14,15,16,18,19,20). This, however, in some cases created the negative association with a weak material, in combination with some small cracks that could have been spotted. This all resulted in that the sample was handled with care since they did not want to break it. Therefore the material was held between four fingers, or sometimes even two hands. Because of this carefulness other ways to hold (grab/grasp/pinch) the sample did hardly occur.

Sensorial material qualities

At the second level, the map was handed over to the participant with a selection of sensorial scales, each opposite characteristics on each side. The participant was asked to rate all the characteristics. The 20 results are shown in figure 51. This figure shows the average (orange) line of all the answers given. The number a rating is given is shown in the picture as well to show the distribution of the answers; did the participants agree with each other? What the participants did agree on was that it is considered a relatively hard material. Furthermore, it is completely matte, not-reflective, not-elastic and opaque. The material is also considered to be light. On all those points at least half of the sample (n>10) gave the same score, which is convincing. 9 out of 20 participants scaled the warmth in the middle, which is also relatively convincing. Participant 18 said, *"it feels warmer than clay but still cooler than the surroundings"*. The 5 remaining properties had more distributed answers. After questioning people found these questions more difficult. Fibers, strength, and toughness are properties that could not be felt or seen, and therefore people did not know what to answer. Participant 3 said: "*it feels light and I see cracks, but maybe you are going to tell me it is the strongest material on earth. I have no idea*". The last 2 scales are the roughness and texture. Although those should be easy to feel, people still did not agree on them. This was because the material itself was considered 'regular textured' and 'smooth' while a 3D print was considered 'irregular textured' and 'rough'. So it mattered if people saw the material apart from the 3D print context, or not. Several participants had a question like: "*do I have to take the fact that it is 3D printed into account, or just look at*

Fig. 50. Results performative level

Fig. 51. Results sensorial level

the material itself?" (participant 2). Since the future application will be 3D printed as well, they were told to take the consequences of 3D printing into account. That is the reason they were given a 3D printed object.

Affective material qualities

For the next step the participant turned the page of the folded map, were an empty graph was found. The participant was asked to choose 3 emotions of a list of 'affective vocabulary' (Figure 53) which s/he thinks the material elicited from him/her. Then they were asked to write them on the graph according to the axis provided; are the emotions more or less intense and are they more or less pleasant. Figure 52 shows all 64 emotions that were elicited from the 20 participants. All the emotions that were placed on (almost) the same spot have been merged. This figure shows that more positive than negative emotions were associated with the material. Every emotion which has been elicited 3 times or more will be discussed. For the negative emotions, these are doubt, boredom, and reluctance. For the positive emotions, these are curiosity, fascination, surprise, and comfort.

Doubt (10x) was mostly elicited because of the small cracks and the low weight. For that reason, people expect it to be weak and therefore doubt it. It was also associated with ceramic which is weak. People also tend to doubt new materials since they can not yet trust them. The last reason mentioned was doubt for possible future applications.
Boredom (5x) because of the grey color, the matte (unfinished-like) texture and the expected limited amount of possible applications.
Reluctance (3x) because the material looked fragile and weak.
Curiosity (11x) and ***Fascination*** (10x) were elicited since they noticed it was an unknown material, and people wonder what it was and how strong it was. Some contradictions were mentioned: 1) low weight for its strength and looks, 2) looks ceramic but feels like something else, 3) looks cold but is warm, 4) looks rough but feels smooth, 5) expect thick but is thin. Furthermore, 3D printing fascinates some people, others asked themselves why you would 3D print such a material.
Surprise (6x) because of the 5 contradictions mentioned above
Comfort (3x) because it is grey, warm and light for its strength it gave people comfort. Some people also described the texture as 'soft'.

Fig. 53. List of emotions

Fig. 54. Set of meanings

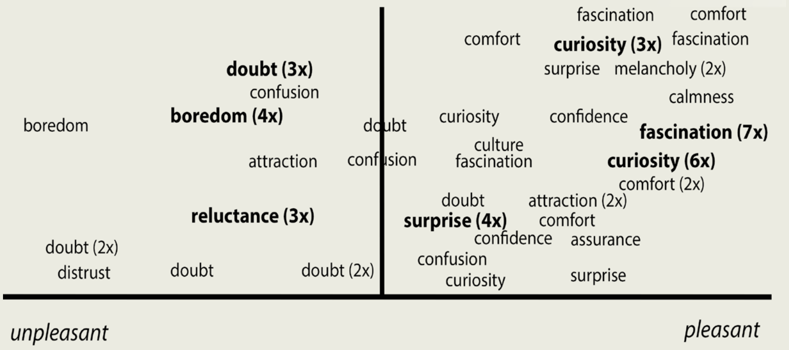


Fig. 52. Results affective level

Fig. 55. Results interpretive level

Natural (15x)
Hand-crafted (13x)
Sober (7x)
Calm (5x)
Strange (4x)
Not sexy (4x)
Futuristic (2x)
Manufactured (2x)
Ordinary (2x)
Toy-like (2x)
Nostalgic (1x)
Elegant (1x)
Cosy (1x)

Interpretive material qualities

In this level, the participant is given the list of meanings (figure 54) and is asked to choose 3 of them and put them on the map. As a next step, they were asked to reflect on those words. Figure 55 shows the 'meanings' that were chosen by the participants, and below, the reflection of the first 6 words are shown. The '+' and '-' show if it is used as a positive or negative description.

Natural(+) was used as a description because the material reminded of earthenware because of its color and texture. Some associated it with paper and wood as well. The layers and colors reminded of nature (like mushrooms). The imperfections and bulges are described as natural and some described the finish as organic.

Handcrafted(+) because the material feels like a handcrafted material and has imperfections/drips. It feels unique like no second product could be the same. It reminded some of their childhood, inviting them to make something with the material.

Sober(-), the grey color, matte finish, cracks, and cement-like texture made it look like a simple and cheap material.

Calm(+) described the smooth surface and low weight. It was felt like a serious material that does not force your attention.

Strange(+/-) because it was a hard product with a soft touch and a light product for its heavy looks. The look and feel do not really match. Strange also described the combination of a new manufacturing technique and (what feels like) an old school material.

Not sexy(-) described the droopy layers and the imperfections. It was also described as old fashioned by some and as a bit dirty by another.

Final reflection

In the final step the participant was asked to reflect on the material by answering 6 short questions; 3 from the toolkit and 3 which are added by the facilitator.

3 Toolkit questions;

"What is the most pleasant quality of the material?"

The smooth, soft and natural texture were mentioned most often. Furthermore, the low weight and imperfections gave it a calm image.

"What is the most disturbing quality of the material?"

The material looked fragile and brittle, cracks were noticed and some disliked the rough grainy texture. Furthermore, the grey color and dirty looks were disliked.

"What is the most unique quality of the material?"

Weight vs strength ratio was mentioned most often. Also, the natural look, smooth touch vs rough looks, warm touch vs cold looks and modern manufacturing method vs 'old' material were mentioned as unique qualities.

3 added questions;

"What kind of products do you expect to be suitable for this material?"

"Do you know what the material is made off?"

"Do you know how the sample is manufactured?"

The last two questions have been added to find out how this knowledge influences the material experience. All 20 participants figured out the product was 3D printed, but just one of them also knew the material since she knew about the previous project by Vette. She admitted that her knowledge made her a little bit more curious because she knew the boring looking material was not boring at all. The fact that the sample was 3D printed contributed to some of them to the feel of curiosity: '*Type of material in combination with manufacturing method seems mismatch in a nice way*' (participant 19). The answers to the first question will be discussed in the ideation phase in the next chapter.

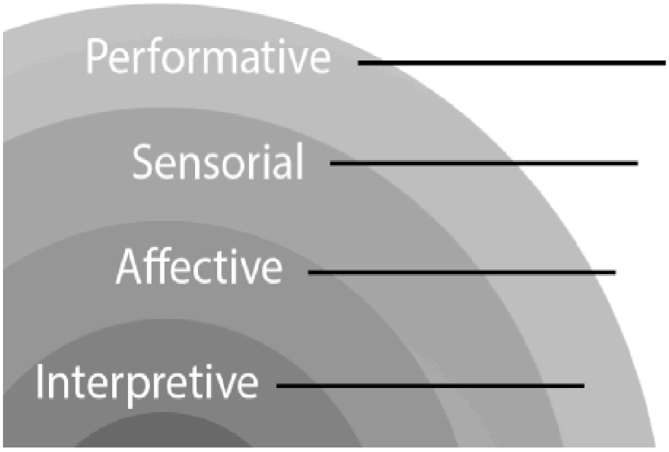
5.4 Discussion

For this user test, some small side notes have to be made. The small sample size (n=20) is enough to give an indication about the experience but is much smaller than sample sizes of tests used to indicate significance (Israel, 1992). Since this test was about giving an idea, instead of creating significance, 20 participants were enough. Furthermore, the material could have been experienced differently if, for example, the composition (mussel/water/alginate) was different than the tested one. For that reason this test used the paste that has proven to give the best print result so far; ratio: 3% alginate / 30% water / 67% musselshell. The shape of the material sample, although designed to show no similarities with other products, had some influence. Many participants turned the sample like a wheel, some of them even admitted they did this because of the shape. People reminded the material sample shape of a (steering)wheel, rim, ants nest, or slices of grapes/oranges. Most participants, however, did not have associations with the shape.

5.5 Conclusion

The material has a handcrafted and natural feel for most people. When picking up the sample, a lot of participants became curious and fascinated since they knew they were engaging with a material they did not recognize. The material was lighter, warmer and smoother than it looked, which was strange but also surprising. The combination of the modern manufacturing technique and the old-looking material was surprising for participants as well. The little cracks, low weight and reminding of earthenware, however, made the material look a little bit weak which is why it got handled with ultimate care and some doubt arose. The color and matte finish made it look sober which bored some people. Although part of the participants disliked the imperfections, the texture, and described it as not sexy, most of them described this as the positive hand-crafted look and natural feel of the material. Because the material is grey, warm, smooth it got described as calm and comforting as well. The uniqueness and positive qualities had to to with the weight-strength ratio, the natural looks, and the surprisingly warm, light, smooth and soft touch. The negative qualities had to do with its fragile looks, the rough texture, and the boring (dirty looking) grey and matte finish. Possible ways to improve those qualities are giving it a (CE friendly) color and design in such a way that the material does not look weak (fewer cracks/imperfections). The finish and textures are difficult to improve (without the use of coating), but since a lot of other participants liked this texture it does not necessarily have to be changed.

As described at the end of chapter 2 (Materials), the acceptance of sustainable materials might improve when the incongruity between visual and tactile properties raise positive surprise (Sauerwein et al., 2017). The incongruity between the visual and tactile properties of this material did raise surprise (, fascination and curiosity), as shown in figure 52. This incongruity can be used as a design strategy because it elicits positive surprise and therefore possibly appreciation (Sauerwein et al., 2017). Figure 56 shows a summary of the outcomes per level.



Handle with care, weighing, rubbing texture, bending, tapping & (com)pressing to test properties.

The material was lightweight and relatively weak & hard. The surface was matte, non reflective and opaque

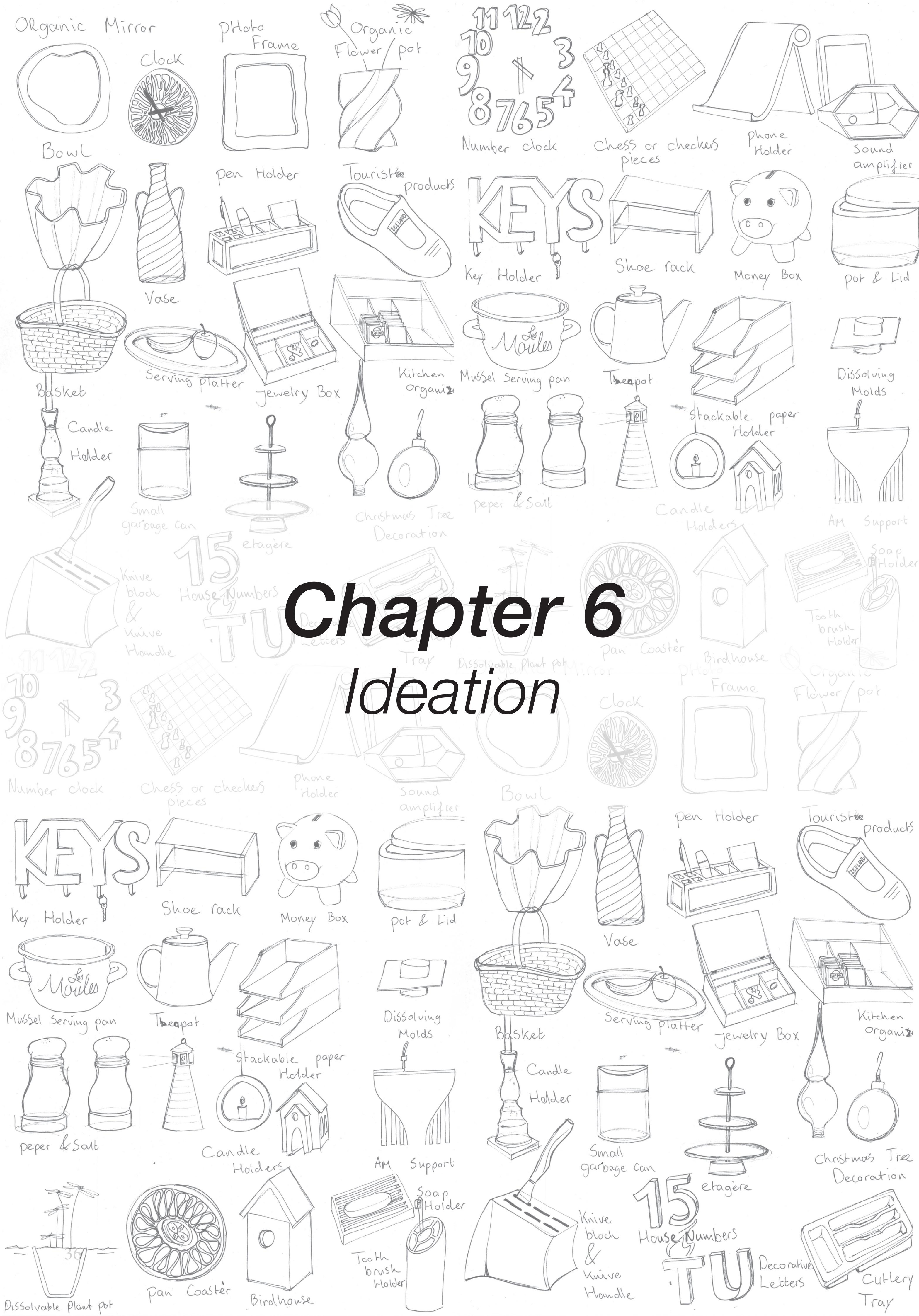
Doubt, boredom & reluctance vs curiosity, fascination, surprise and comfort.

The material was described most often as being natural and hand-crafted. Other descriptions: sober, calm, strange and not sexy.

Fig. 56. Swummary of outcomes per experience level

Chapter 6

Ideation



6.1 Introduction

This chapter describes the ideation phase. This part should, however, not be seen as the last part exclusively, because thinking about ideas already started after making the first print. As Karana explains in the MDD method the ideation phase already started when optimizing and testing the material; "even after just Step 1, the designer might already have an idea for an application (product) domain.' (Karana et al., 2015). This chapter works from these ideas towards a chosen concept. To get some structure in this phase, this chapter is divided into 7 parts:

1. *Defining the requirements and wishes.*
2. *Elaborate 'applications question' from chapter 5.*
3. *Convert chapter 5 outcomes to 'How to's'*
4. *Individual brainstorm, based on the 'How to's'.*
5. *Brainstorms in groups, based on the 'How to's'.*
6. *Converting these ideas into 3 concepts.*
7. *Choose the final concept based on Harris profile.*

6.2 Requirements and wishes

A list of requirements states the important characteristics that the final design must meet in order to be successful (Boeijen et al., 2017). The list of wishes will be used for tools in the decision phase. All the insights gathered in this thesis so far have had an influence on the requirements and wishes the final application should meet. Since in this chapter a final concept will be chosen based on the requirements and wishes, it is essential to define them. The most important ones are placed at the top (figure 57). The reasons for choosing these requirements and wishes will be discussed below the figure.

Requirements

As explained before, the goal of this thesis is "to design and create a 3D printed product with alginate-mussel paste that lasts at least 2 life cycles". To reach this goal it is of importance that the product can be printed within the 20 weeks of this project (R1), it will be done with the available Ultimaker Extended2+ (R9) and fits within the Ultimaker dimensions (R6). One of the biggest limitations of the material is stability during printing (R7) and one of the biggest opportunities is the possibility to cross-link (R8). Furthermore, the goal describes the requirement of lasting at least 2 life-cycles (R2) to show the recyclability of the materials. At last, this project is a combination between AM (R4), a CE (R3), and a new biobased material (R5), and therefore the concept needs to show good reasons for how those 3 project pillars are met.

Wishes

4 wishes are the superlative of a requirement; multiple life cycles (W2), multiple reasons for AM (W4), multiple reasons for a CE (W3) and multiple reasons for this biobased material (W5). These are wishes because the more matches a concept has with those '3 project pillars', the better. Furthermore, the most important wish is to create an innovative application (W1), because with this thesis I would like to create something that does not exist yet. The most unique part of the concept will be the material, which is made from recycled mussel shells. To spread this idea of sustainable design, it is desired that a lot of different people get in touch with the application (W7), and preferably as much contact as possible (W6).

Requirements	**Wishes**
1. Manufacturing the product is feasible within the project time.	1. It is an innovative application
2. Lasts at least two life cycles.	2. Lasts multiple life cycles
3. Has at least one new match with the CE.	3. Has multiple matches with the CE
4. Has at least one good reason for AM.	4. Has multiple good reasons for AM
5. Uses at least one material characteristic.	5. Uses multiple material characteristics
6. Fits within 215 x 215 x 300 mm (XYZ).	6. Amount of physical user interaction
7. Does not collapse during printing.	7. Interaction with many different users
8. Cross-linking is needed.	
9. Possible to print with an Ultimaker 2+ extended.	

Fig. 57. Requirements and wishes

6.3 Experiential characterisation

The first product ideas that will be discussed in this chapter are the ones that were mentioned by the participants of the user test in the previous chapter. In the 'final reflection' part of the toolkit, one of the added questions was "What kind of products do you expect to be suitable for this material?" Although not every participant did have an idea, the ideas that were given are shown in figure 58 and 59. Figure 58 shows the amount of time certain ideas were mentioned and figure 59 visualises these ideas.

Ideas	**Amount**
vase	4
bowl	4
visual home decoration	3
plastic replacement	2
art	2
gypsum replacement	1
bone substitute	1
toys	1
tableware	1
animal crib	1
wall filler	1
floor tiles	1
picture/painting frame	1
construction sector	1
ashtray	1

Fig. 58. Ideas from user test

Fig. 59.Visualisation of ideas of participants

6.4 How-to's

The output from the experiential characterisation user test and the known technical material characteristics will serve as an input for the brainstorms. This will be done by translating these outcomes into 'how-to's' (figure 60, Boeijen et al., 2017). By doing this, applications that match these characteristics can be found.

How to's experiential characterisation
How to make something look natural?
How to make something look hand-crafted?
How to give something a warm or soft feeling?
How to personalise a product?
How to's technical characterisation
How to make something look strong or fragile?
How to use a rough texture/imperfections
How to reduce weight?
How to dissolve or recycle a material?

Fig. 60. How to's based on experiential and technical characterisation

6.5 Individual brainstorm

Brainstorming is a method that is used in the MDD method to create a big amount of ideas, and the different steps are described in the Delft Design Guide as well. In brainstorming 3 media can be used; speaking, writing and drawing. When using 'speaking' as a medium a group of 4-8 participants is used most often and a facilitator asks provocative questions based on a problem statement and writes down the group's responses on a flip chart. This is the most popular way of brainstorming. Due to experience with this method, however, I know that it can be difficult to create a safe and secure atmosphere with a group of complete strangers when using 'speaking' as a medium. Often the ideas come from 1 or 2 participants, while some others do not open their mouths. For that reason, writing and drawing as a medium is chosen. These variants are called 'brainwriting' and 'brain drawing' (Boeijen et al., 2017). These methods create a safer and more secure atmosphere (for the bit more shy participants) which improves the generation of ideas. These methods will be explained further in section 6.6. As a pilot, this method was tested, before starting to generate ideas with other IDE students. In this way, the potential of the How-to's can be tested. Figure 61 shows the individual brainwriting session, based on the how-to's. The ideas generated in this session will be shown in figure 63.

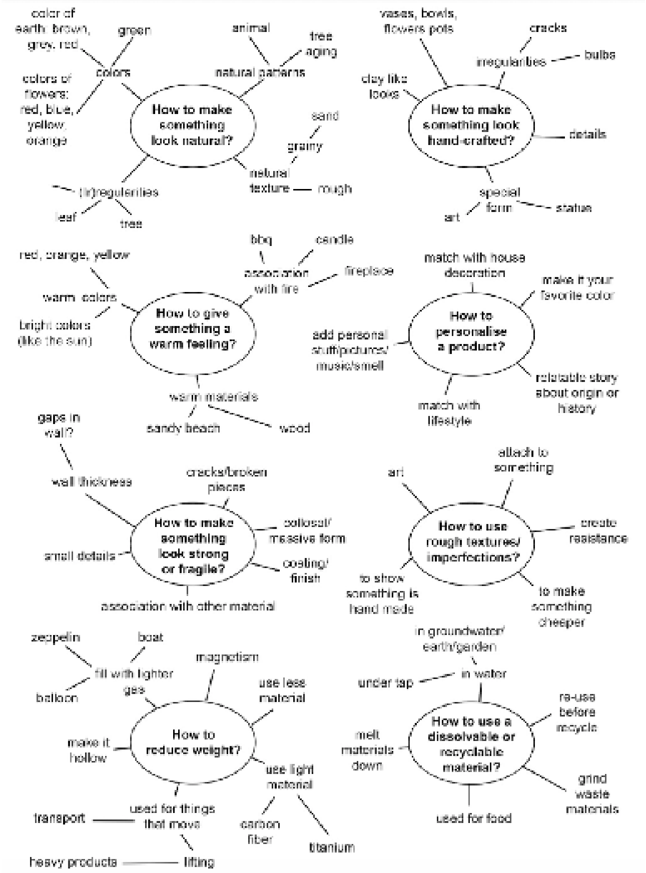


Fig. 61. Individual brainwriting session

6.6 Brainstorm in pairs

Figure 61 proves the 'how-to's' can give enough input to start a valuable brainwriting and brain drawing session. However, during the group session, the 'how-to question' seemed to make the brainstorming more difficult; there was a lot of input, but the answer on a 'how-to question' gives the wrong direction. This is because the idea of this brainstorm was to create ideas that match the material characteristics, not to create ways to achieve this characteristic. For example; the answer on 'how to reduce weight?' might be 'use less material', which does not create a creative session towards product ideas. When you brainstorm about 'Lightweight products', the answer might be 'air transport' or 'orthoses', which are possible product ideas. Therefore, the group session brainstorms based on the material properties itself (i.e. 'Natural products' instead of 'How to make something look natural?'). To increase the number of ideas this brainwriting session will be performed in 3 pairs of IDE students, 6 participants in total. Since participants are not directly reacting on each other there is no necessity to create bigger groups. Therefore groups of 2 people are made. Karana used groups of 2 or 3 in the MDD method for similar reasons. Figure 62 shows the setup of the brainwriting and brain drawing in pairs.

Fig. 62. Brainwriting and brain drawing in pairs

Method

Both participants were given a hand-out, each displaying 4 different properties. After discussing the 4 golden rules of brainstorming (figure 62), the participants were asked to write down anything that came in mind when seeing these product properties. After 5 minutes the handouts were switched and the participants were asked to continue on the brainwriting of the other participant (to increase the value of ideas). After the brainwriting, a sample of the material was provided and an explanation about the technical and experiential properties of the material was given. At this moment they noticed the product properties on the handout matched with the material properties. The last part of the session was the brain drawing. The participants were asked to create 2 or 3 ideas, based on their brainwriting handout and the technical and experiential properties. Afterwards, the papers were swapped again to add to each other's ideas. In the last step of the session, the participants explained their ideas, which ended the method with a small discussion. Appendix 6 gives an overview of all the ideas generated in the group session. Figure 63 visualises the collection of all the ideas generated so far, created with the toolkit and the brainstorms.

Fig. 62. Golden rules of brainstorming

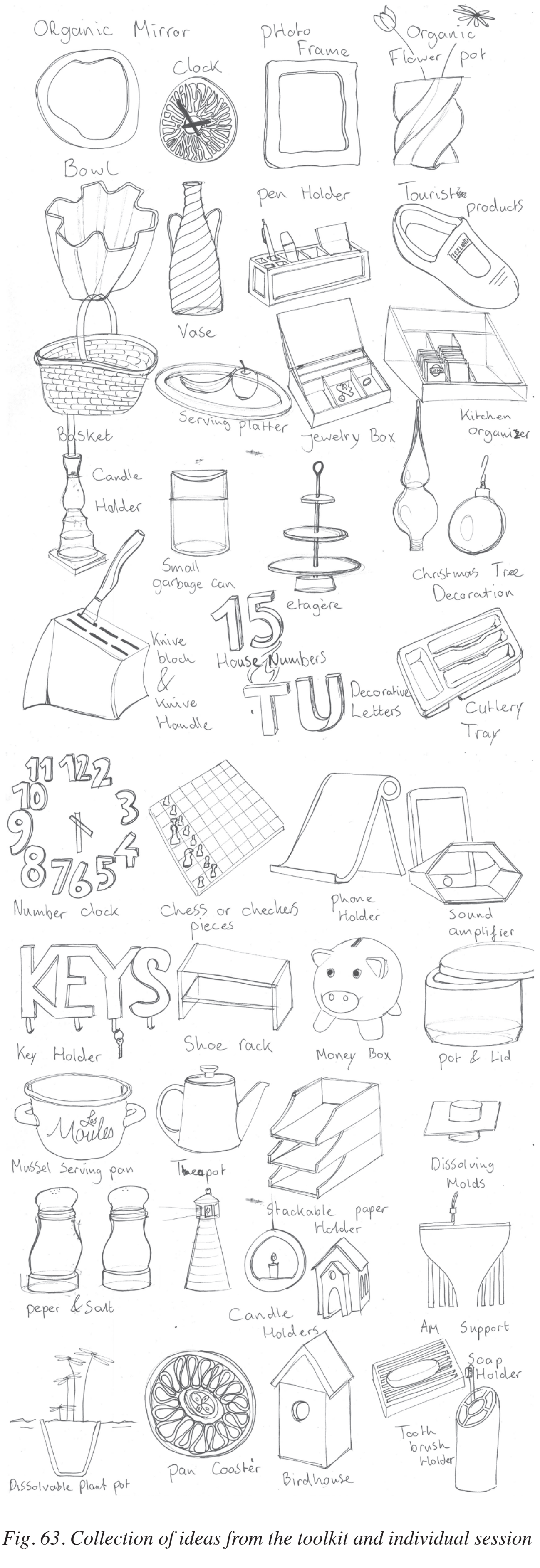


Fig. 63. Collection of ideas from the toolkit and individual session

6.7 Towards 3 most suitable concepts

The last golden rule of brainstorming reads; ‘quantity over quality’. The underlying idea is that ‘quantity breeds quality’ (Boeijen et al., 2017). However, none of the individual ideas generated before has enough potential on its own. These ideas were based on the look and feel of the material, but some important requirements (figure 57) have not yet been taken into account. For that reason, a brainstorm was performed (figure 64) about the requirements to fit with the material, a CE and AM. This brainstorm was based on the findings from the literature research (chapters 1-3).

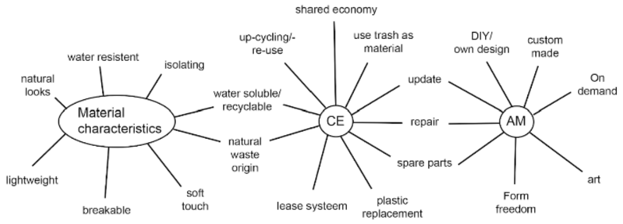


Fig. 64. Collection of ideas from the toolkit and individual session

Based on this brainstorm session another look on the +/- 40 generated ideas was given. Although quantity is needed to breed quality, a lot of the ideas did not match entirely with 1) the characteristics of the material, 2) the CE or 3) AM. The main reason for using alginate as a binder is the possibility of reversible crosslinking to make the material water-resistant. Using the material for an application that does not get in contact with water is, therefore, a lost potential. For those applications, the ‘old paste’, with sugar as a binder, would have been sufficient. When removing all the ideas from figure 59 which does not have any reason for cross-linking or AM, there are 9 ideas that remain. Appendix 7 describes those 9 ideas, but this time with more emphasis on the matches with the material, the CE and AM (figure 64). Although the most obvious link between a CE and AM, as shown in the figure, is an update, repair, or spare parts, almost none of the 9 ideas use this as an input. That is because, combined with the material, it seemed quite difficult to match with the material. Products in which spare parts are needed are relatively detailed, and spare parts that have to fit perfectly will be almost impossible to create with this paste. An update or repair does mean that an extra part will be printed and integrated to improve a product, which is a level of detail that probably can not be achieved with this material. The 9 ideas are shown in figure 65 and described on the next page.

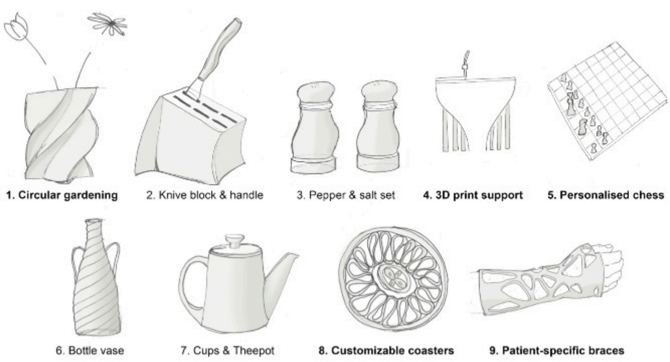


Fig. 65. 9 selected ideas

Circular gardening is a flower pot which is a great match for the material because both the sodium alginate and calcium carbonate has a positive influence on plant growth. The pot can be watered because of the crosslinking. When broken it can be returned to the garden center in return for another one, or for money, which makes it circular. The circular aspect is shown in the design as well.

Knife block & handle can be 3D printed, of which the 3d printed handle fits perfectly in somebody's hand. The material's soft touch is perfect for a handle, and the knife can be washed because of the crosslinking.

Salt & pepper is an idea in which the material is used to keep away moisture from the salt & pepper. The soft-touch makes the use pleasant. This product replaces plastic supermarket packaging and can be designed according to its user's desires.

3D print support with mussel shell paste is a great match for AM and replaces plastic support. After use it can easily be washed away.

Personalised chess is an idea in which chess stones can be designed by the user, or used as tourist products. When a part is broken, only one has to be reprinted to complete the set again. The soft-touch of the material matches with toys.

Bottle vase is a carafe that also can be used as a vase. The product can be put in another use, and therefore people might want to use the product longer. Furthermore, the natural look of the material matches the application.

The cups & the pot is an idea which can be personalised by the user. The material isolates the heat from hot drinks, and the crosslinking makes this application water resistant.

Customizable coasters, for example, pan coasters, the pot coasters or cup coasters, isolate the heat from the table surface. Restaurants (for example) can use the AM to use it for marketing (print a logo in it). The soft material makes no scratches on the table surface, and the crosslinking makes it water-resistant, so spilling a drink on it, or cleaning it, is no problem.

Patient-specific braces is probably the idea with the best reason for AM, since a customised brace can be printed based on the scan of a patient's arm. This brace helps to recover broken bones in the arm, and the breathing holes make the usage less sweaty and itchy. The soft-touch is pleasant on the skin, and the low weight is useful for something which has to be carried around all day.

Out of these 9 ideas, 5 ideas with the most matches (appendix 7) are in bold in figure 65; circular gardening, salt & pepper set, personalised chess, customizable coasters, and patient-specific braces. All 9 ideas were mapped in a C-box to evaluate on the most important wish and requirement; innovativeness and feasibility, as figure 66 shows. Below the figure the placement in the C-box is justified.

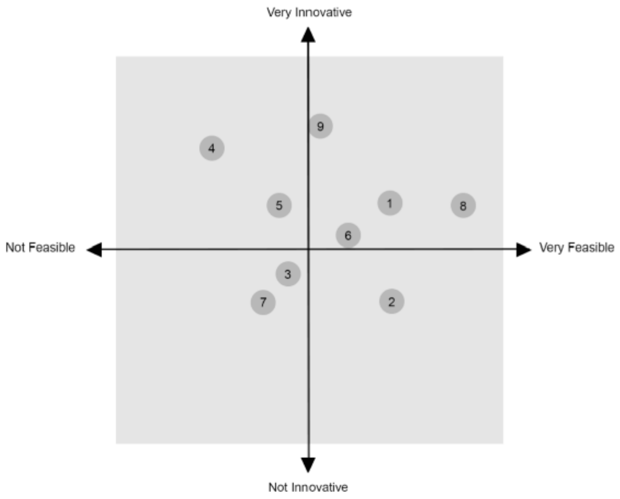


Fig. 66. 9 selected ideas

In this map innovative means how different the idea is from existing products. Feasible means 1) how likely it is it can be 3D printed with an Ultimaker and also 2) if the idea itself is feasible; will it work? For those reasons, the 4 ideas in the upper right quarter are most desired, which will be discussed below.

Circular gardening (1) is relatively innovative since a lot of flowerpots do exist, but none with these combined characteristics (which will be explained later on). Because of a special Cura mode called 'spiralize outer contour', the shape is a good match for 3D printing the paste which makes it a feasible idea.

The Bottle vase (6) has a combined functionality which makes it relatively innovative as well, but since it is rather tall and small at the top the feasibility is somewhat lower than the first idea.

The Customizable coasters (8) for pans, teapots and cups/glasses do already exist, but the idea that you can design them yourself is new, as well as the kind of material for this kind of applications. The print is really low and therefore feasible to 3D print.
The Patient-specific braces (9) is quite innovative since a ceramic-like material has never been used for 3D printing such an application. The hollow shape, however, will be a challenge to 3D print and therefore the feasibility is low.

Ideas 3, 4, 5 & 7 were considered less feasible. Those reasons will now be discussed. Although the ***salt & pepper set*** (3) matched well with the material, the idea is not feasible since the attraction between salt (NaCl) and water molecules is stronger than the attraction between sodium-alginate and water molecules (CES EduPack), meaning the material will not manage to keep the salt dry. The ***3D print support*** (4) is not really feasible since the material is more difficult to print than plastics, and is therefore not the best support material. On top of that, dissolvable plastics are already used for this purpose (Pei et al., 2015). ***Personalised chess*** (5) is less feasible because the details needed for chess stones (or other toys) can probably not be achieved with this material. During the material experience research, participants pointed out that the material is not comfortable to put on your lips, which is why the ***cups*** (7) are less feasible. ***The teapot*** (7) has as biggest issue that it should be able to carry the weight of a liter of water, which might become difficult when the material is flexible because of the hot water. ***The knife block & handle*** (2) contain no complex shapes, which is why the feasibility is rather high. A knife block, or organically shaped knife handle, already exists, which is why it scores low on innovativeness.

Based on the C-box and the matches (with CE, AM and material characteristics) 3 ideas were chosen to develop as concepts in part 6.8: Circular Gardening, the Patient-specific braces, and Customizable coasters. These 3 concepts were chosen because in both decision-making tools (appendix 7 & fig. 66) they ended up among the best concepts.

6.8 Towards the final concept

6.8.1. Concept 1: Circular gardening

This concept is a multifunctional flower pot for garden centers and for people at home. It combines the functionalities of a porous terracotta pot, biodegradable cups and the aesthetics of an earthenware flower pot. This product, therefore, matches with the 'narrow loops' strategy (section 3.2), since the combined functionality takes over the use of other pots. Because this concept drains excess water, see figure 67, plastic inserts (with the same functionality) do not have to be used at home anymore, so this product also diminishes plastic use.

The material is a good match for this concept; when the plant in the pot receives water, the pot turns a little bit flexible but does not dissolve because it is reversible cross-linked. Because it is resistant to rain it can be used outdoors as well. When wet, the calcium carbonate (which is used as soil fertilizer) now helps to neutralize acids (oxalic acid), which prevents plant poisoning. Furthermore, calcium carbonate improves the soil and the intake of nutrients (Jones., 2012). For that reason, some extra nutrients can be added during the printing process. Because of the 3D print ridges, the contact surface is quite large which is beneficial for this process. When by accident too much water is given, the excess water is absorbed by the material of the flower pot (just like with a terracotta pot), so the flower's roots will not rot. This excess water later on evaporates or is returned to the plant. Except for the capabilities of the material, it's natural look and feel matches a flower pot very well as well.

When broken (or when it is not liked anymore) the product can be returned to the garden center in return for another one, or for money. At that point, the garden center recycles the material to use it again, which meets the 'Close loops' strategy. AM is used to give the flowerpot a design which can only be achieved with AM. As an additional service the garden centers can let their clients design their own flower pot online. AM can also be used to make a plant-specific pot to increase the growth rate.

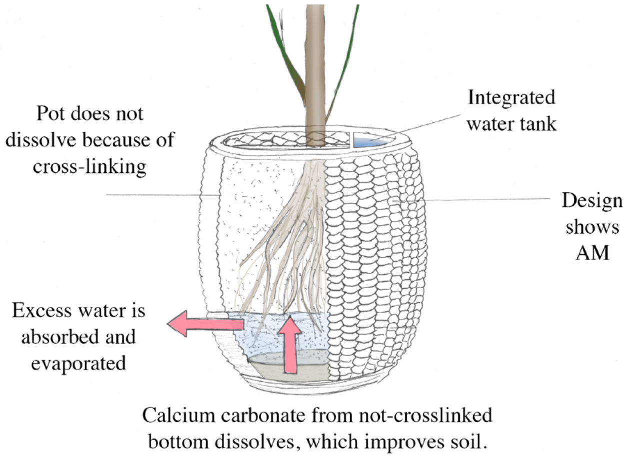


Fig. 67. Concept 1: Circular gardening

6.8.2. Concept 2: Customizable coasters

Other material characteristics are the soft touch and the isolating effect which are a good match for coasters for, for example, cups, teapots, and pans (figure 68). Furthermore, the water-absorbing material prevents moisture from dripping on your furniture (Cavanauch., 2019). The material isolates the heat from the teapot, pan or cup and makes sure it does not burn the tabletop. Because the material is really soft it will not make scratches on the tabletop either. Since the material is water-resistant, spoiling water on the coaster is no big deal. When the coaster gets dirty because some food is spoiled on it, the coaster can be cleaned without it dissolves.

This concept is meant for hotels, apartments, and restaurants from the tourist sector of Zeeland who would like to show that they care about reducing Zeeland's waste stream and a circular economy, but of course, the coaster can be bought by individuals as well. When preferred a companies logo can be integrated because of the form-freedom of AM. Other materials that can be 3D printed do not have great isolating properties (like metal) or will melt because of the heat (plastics). For that reason, this material will be a good match for this purpose. AM can be used to reduce the amount of used material, which matches the 'narrow loops' strategy. When restaurants or individuals return the discarded coasters to a 3D print company, the 'close loops' strategy can be used as well.

6.8.3. Concept 3: Patient-specific braces

When someone's arm is broken it needs to recover. Nowadays a broken arm gets wrapped in gypsum and bondages. This, however, has the disadvantage that it is not comfortable; it becomes itchy and sweaty and it can not be cleaned.

By 3D printing, it will be possible to leave some holes so it does not get itchy and sweat, and AM can be used to support only on the spots where it is really needed, figure 69 shows this concept. 3D printing also helps to make the perfect fit for somebody's arm, since AM is known for custom made designs. By scanning your arm in the hospital a 3D model based on this scan can be realised. Since the brace needs to exist of 2 parts, only half of the product has to be re-printed when it gets accidentally broken. This matches the 'slow loops' strategy. Leaving holes where no material is needed matches the 'narrow loops' strategy, and since (some) hospitals/orthopedic centers already have their own 3D printer, it matches the 'close loops' strategy as well.

The material is a good match for this concept as well since you can take a shower and wash your arm, without dissolving the brace, and walking outside in the rain is not a problem either. The soft-touch and warm feeling of the material will be pleasant on the user's skin. Furthermore, the material is really light which is a benefit for something you have to carry around all day. When the bones are healed after 6 weeks the material can be broken off the arm with force and the pieces are returned to the hospital. Another possibility is to go to the hospital and immerse your arm in a bath filled with sodium ions, so the brace becomes water-soluble and it can be washed away. In both solutions, the hospital (or orthopedic center) can use the material again to make a print for somebody else.

Fig. 68. Concept 2: Customizable coasters

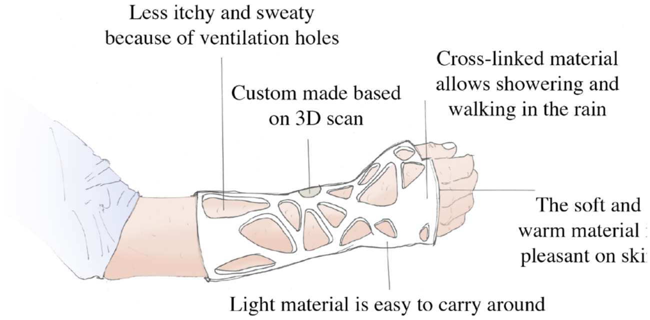
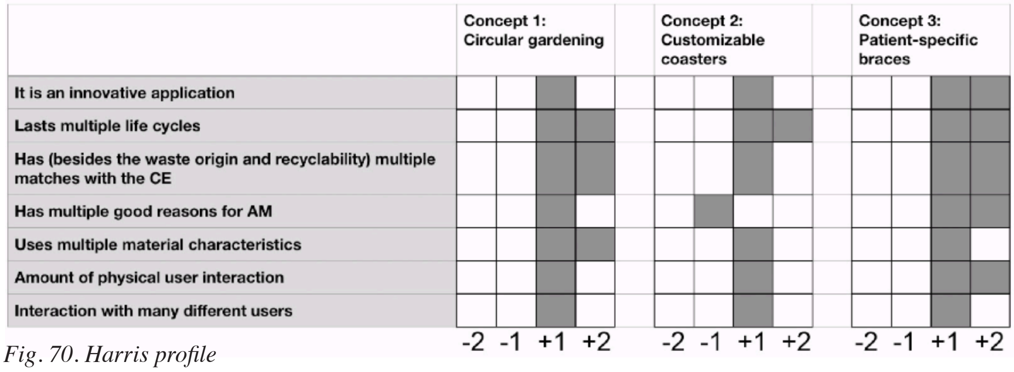


Fig. 69. Concept 3: Patient-specific braces



	Concept 1: Circular gardening				Concept 2: Customizable coasters				Concept 3: Patient-specific braces			
It is an innovative application			▨				▨				▨	▨
Lasts multiple life cycles			▨	▨			▨	▨			▨	▨
Has (besides the waste origin and recyclability) multiple matches with the CE			▨	▨			▨				▨	▨
Has multiple good reasons for AM			▨			▨					▨	▨
Uses multiple material characteristics			▨	▨			▨				▨	
Amount of physical user interaction			▨				▨				▨	▨
Interaction with many different users			▨				▨				▨	
	-2	-1	+1	+2	-2	-1	+1	+2	-2	-1	+1	+2

Fig. 70. Harris profile

To choose the final concept from those 3 concepts, a harris profile was created to visualise how the three concepts scored on the 7 product wishes. The outcome is shown in figure 70. Below the figure, an explanation of the rating is given.

Innovative
The most important wish is the innovativeness of the application. In this figure, innovative means how the idea differs from existing products. As discussed in figure 62, concept 3 is the most innovative one, and concepts 1 & 2 are more or less on the same level. Therefore concept 3 gets +2, and the other two +1.

Multiple life cycles
Since the CE is of high importance to this project, the amount of cycles is of high importance as well. Since none of the concepts has a reason why the life cycles will be limited, they all got awarded a +2.

Matches with CE
For the matches with a CE, the 4 strategies from section 3.2 are used. When applicable, these strategies are matched with a concept, as read in section 6.8. As explained in 6.8, concept 1 matches ‘narrow loops’, ‘slow loops’ & ‘close loops’. Concept 2 matches ‘narrow loops’ and ‘close loops’. Concept 3 matches ‘narrow loops’, ‘slow loops’ & ‘close loops’. Therefore, concept 1 and 3 get rewarded ‘+2’, and concept 2 ‘+1’.

Matches with AM
Concept 3 uses AM to make very detailed & custom made parts and gets, therefore, a +2. Concept 1 uses AM to make plant-specific plant pots; custom made, but no need for detail, it gets rewarded +1. Concept 2 only has design as a reason for AM, which is why it receives a -1.

Matches with the material
Concept 1 uses 4 material characteristics; soil fertilizer, absorbing water, natural look, and insolubility. Concept 2 uses 3 material characteristics; soft, isolating and insolubility. Concept 3 uses 3 material characteristics; soft, lightweight and insolubility. Therefore the rewards are +2 for concept 1 and +1 for concepts 2 & 3.

Physical user interaction
This means how often the user gets in touch with the concept. Concept 3 is on your arm permanently and therefore gets a +2. The other 2 concepts will be used every now and then, and therefore each get a +1.

Different users
Will it be used by many different people or only a select group? The target groups of the 3 concepts are expected to be more or less on the same level, which is why they all got a ‘+1’.

6.9 Discussion

As shown in figure 64 and discussed in chapter 3, the CE and AM are a good match for repairing products, creating spare parts or giving products an update. Combined with the material, however, this seemed quite difficult to match. Products in which spare parts are needed are relatively detailed, and a spare part which has to fit perfectly will be almost impossible to create with this paste. An update or repair does mean that an extra part will be printed and integrated to improve a product, which is a level of detail that probably can not be achieved with this material. However, one of the three concepts; the patient-specific brace, can make use of both an update (when it does not fit well enough) or repair (when a part is broken). It remains a question if this concept can be printed though.
During ideation and searching for inspiration chalk (gypsum) seemed to be used for construction a lot. Mussel powder is almost 100% chalk, so a suitable application in the world of construction could be found. The reason why this idea is not chosen is because the Ultimaker (one of the requirements) is too small for those applications and the material is probably too expensive to use in big amounts.

6.10 Conclusion

Based on the wishes, concept 3 had the best score (figure 70). This concept, unfortunately, also has the lowest feasibility (figure 66) of the 3 concepts, because the shape might be hard to print with this material. Therefore, next chapter will try to get a proof of concept for concept 3.

Chapter 7

Proof of concept

7.1 Introduction

As described in the previous chapter, concept 3: the patient-specific brace, was considered to be the most suitable of the three. However, since it appears to be the least feasible concept as well, a proof of concept needs to be found before taking any further steps. This chapter focuses on finding proof that it is feasible to 3D print the aforementioned concept.

7.2 Existing orthopedic braces

The idea of 3D printing a brace (or orthose) with the mussel paste is considered to be less feasible because of the hollow shape. Even when printed in 2 parts, it needs support to print the convex shape. The low stability makes the material unsuitable as support material, which is why another approach is desired. After a background check on existing 3D printed braces, it appeared that a big disadvantage of this method is the long printing time (Fitzpatrick et al., 2017). For that reason it was decided to use one of the material properties to solve this problem; the material's flexibility after crosslinking. By 3D printing the shape in 2D, printing times will be decreased drastically and a big disadvantage of the current method could be solved. However, after having a further look into the disadvantages of the current 3D printed braces, it appeared this was not a cutting-edge idea. In august 2019 researchers from the University of Bucharest proposed 'a new solution for producing customized 3D-printed flat-shaped splints, which are then thermoformed to fit patient's hand' (Popescu et al., 2019), shown in figure 71.

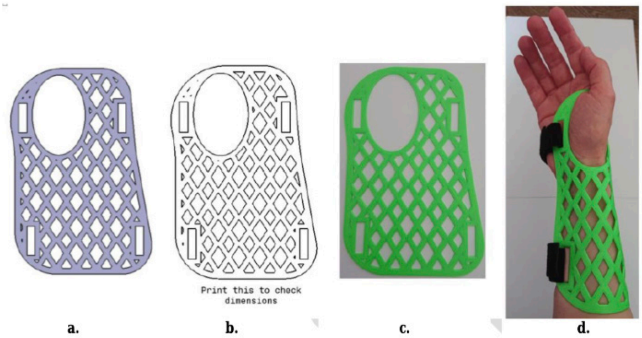


Fig. 71. Thermoformed splint made by the University of Bucharest researchers (Popescu et al., 2019).

7.3 Proof of concept; material flexibility

Despite the fact that the idea is not brand-new, it still is a proper match with the material because of its low weight, soft touch, and flexibility. Flexibility must be proven first to obtain a proof of concept. The flexibility of the material was obtained after cross-linking in a 3% calcium chloride (CaCl) bath, as shown in figure 72.

Fig. 72. Cross-linking process

For this test, an old, unused, sample of the experiential characterisation test was used. After the material was kept in the CaCl bath for half an hour, it was carefully placed on a hand, and slowly submerged in a sink filled with water. After 10 minutes the material was checked, and it was noticeably more flexible, but despite the caution, the material broke on its weakest points (figure 70). Fortunately, the sample seemed to be unfitting for this test because of the thickness; a thicker sample has more internal stresses and therefore a higher chance of breaking. Figure 73 shows that the material can be really flexible when only 2 layers do have to bend (right), instead of 10 layers (left). For that reason, another test was carried out, with a thinner sample.

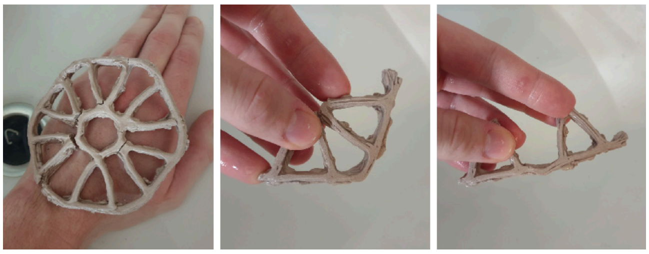


Fig. 73. Flexibility fail & flexibility proof

For the second test, a sample had to be created with fewer weak points, which is why the grid of figure 74 was created. A product with holes in it will always have weaker points, but this consistent zig-zag pattern at least divides the stresses over the whole grid. Figure 74 shows that this 3 layered (=3.6mm) cross-linked grid showed fewer cracks that the previous test, although cracks were still visible (figure 74.4 & 74.5). Submerging the sample a second time for 10 minutes, but now in hot water, made it even more flexible.

Fig. 74. Second flexibility test

This resulted in a 180 degrees bend (figure 74.6). Even with hot water, and extreme caution, cracks appeared in the material. Since more and more doubts about the feasibility of this concept arose, it was decided to use the expertise of an expert: Wybren ten Cate from the Orthopedic Centre Rotterdam.

7.4 Visit Orthopedic Center Rotterdam

A visit to Rotterdam's orthopedic center was executed to ask a professional about the value of this concept to his branch. This visit made clear the center was in a transition phase; from old school plastering and gypsum with many positive and negative molds, towards 3D printed braces, casts, molds, and orthoses. He also explained that there are many different cases, each with different approaches, methods, and materials. In some cases, the 'old way' was still preferable, and another time 3D printers could do the job better. Appendix 8 gives an impression.

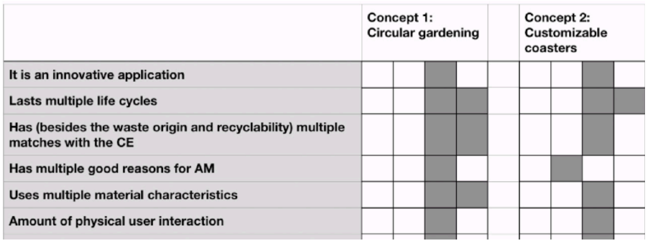
When talking about this concept, Wybren explained that folding a 2D shaped object around body parts (mostly wrists) was already being used, mainly as temporary solutions before an orthosis is ready. Orthoses differ from casts/braces; an orthosis is worn permanently, for example by somebody with spasms or artrose (to much tension on tendons), while casts (or braces) are temporarily and used for healing broken bones. Wybren suggested using this material as a replacement for a material they currently use (figure 75) to keep a patient's arm with spasms steady while 3D scanning the arm. For this idea, however, the material needs do dry really quickly and should be strong enough (without cracks) to keep spastic movements in control. The original idea, making a brace to heal broken bones, had as most important requirement the strength as well.

Fig. 75. Applications to fixate a spastic wrist while 3D scanning

This discussion, unfortunately, made clear that the desired material properties (strong and fast drying) did not match our developed biobased mussel paste. Combined with the fact that the idea is not as innovative as previously thought (it already exists), the material becomes weak under the shower and that the material absorbs sweat and will start to smell, this concept did not seem feasible after all. Since the chances of improving the material's strength within the remaining project time, or changing the concept so that the current material is strong enough, are very low, there had been decided to go for another concept.

Choosing a new concept

For that reason, another look was given at the harris profile (figure 76). As can be seen, concept 1 scores better, caused by wish 2, 3 & 4. Concept 2 has fewer matches with a CE, AM and the material than concept 1 has (appendix 7). An idea was initiated to change concept 2 from a 2D to a 3D concept, like figure 77 (cgtrader.com). Even though it is a more challenging and interesting product, the matches with a CE, AM and the material are unchanged. Therefore concept 1 (circular gardening) is the new concept to develop.



	Concept 1: Circular gardening				Concept 2: Customizable coasters			
It is an innovative application			■				■	
Lasts multiple life cycles			■	■			■	■
Has (besides the waste origin and recyclability) multiple matches with the CE			■	■			■	
Has multiple good reasons for AM			■			■		
Uses multiple material characteristics			■	■			■	
Amount of physical user interaction			■				■	

Fig. 76. Harris profile

Fig. 77. Concept 2.2

7.5 Proof of concept circular gardening

The biggest issue of printing a planter is it's height. Chapter 4 focussed on changing the printing setup in order to print a more viscous paste. Pastes with only 27% water were printed, as shown in figure 78. To achieve this, not only the new setup (figure 39) was needed, but another look at the nozzle size was required as well. Other researchers and designers using material extrusion to 3D print ceramics used way bigger nozzle than we did (around 5 mm). Since our nozzles were not that big, a test was carried out; 3D printing without a nozzle (3.5mm instead of 1.5mm) which is shown in figure 78. However, since it was discovered that layer adhesion became worse when printing with only 27% water, it was decided to use 30% water for the next prints, 27% weakened the print too much.

Fig. 78. Printing a 100mm tall object

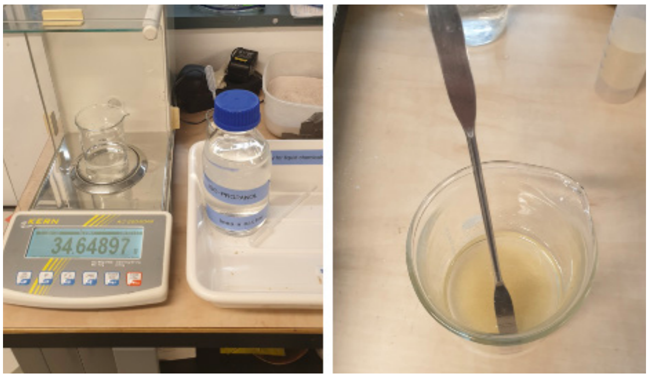


Fig. 79. Test with isopropanol

As another approach to dry the material, but keep layer adhesion, it was tested to print with adding a very fast evaporating substance (Isopropanol), to increase the drying process. Instead of using 30% water, a 20% water and 10% Isopropanol solution was created. Unfortunately, the alginate did not form a gel with the water anymore because of the addition of isopropanol (figure 79), so the test was no success.

A third test was carried out to prove one of the properties of this concept; solubility vs insolubility. Does the inner pot really dissolve when water is added, so that nutrition reaches the plant? And does the cross-linked outer pot stay untouched? Figure 80 shows a cross-linked basin on the left and a non-cross-linked basin on the right. After adding some water, the non-cross-linked basin started dissolving and therefore could not hold the water which leaked on the paper. The cross-linked basin kept the original amount of water and did not deform or dissolve. The 2 pictures were taken 10 minutes after each other. This test shows the inner pot should be able to dissolve when water is given.

Fig. 80. Effect of water on cross-liked and non-cross-linked prints.

The test shown in figure 80 shows that non-cross linked material can be used to create an inner pot that dissolves and therefore gives its nutrition to the plant's roots. This means the user has less work on their plants. For that reason, it was decided to make a plant-specific planter for people who do not have the time or skills to care for their plants. It is a relatively cheap alternative for the 'smart planters' with integrated sensors and electronics. To find out more about the care of plants a visit was made to the 'plant asylum' of Delft, a place where people bring their plants which became undesired or almost died. Xandra explained that half of the visits were made by people with a dying plant. The main reason why plants die was, according to Xandra, overwatering; when people think something is wrong with a plant they give more water, which eventually drowns the plant and lets its roots rot. For that reason, the idea of a water funnel was created, to prevent overwatering. Other possible dead causes were; not enough nutrition, illumination or oxygen, or the pot was too big or small for the plant.

7.6 Designing a plant-specific planter

Every plant requires unique plant care, which is why some people have difficulties keeping their plants alive. Xandra gave 5 most occurring dead causes of plants. These 5 aspects were taken into account when designing the 3 parts of the plant-specific planters; outer pot, inner pot, and watering system. This section explains how AM can help to make plant-specific designs, using 3 popular plants as an example. They were selected since they were in the top 10 of the most popular Dutch indoor plants (2019) and flowers (Variavoer.com). To demonstrate the parametric design principle, 3 plants with different characteristics were chosen, which are shown in figure 81.

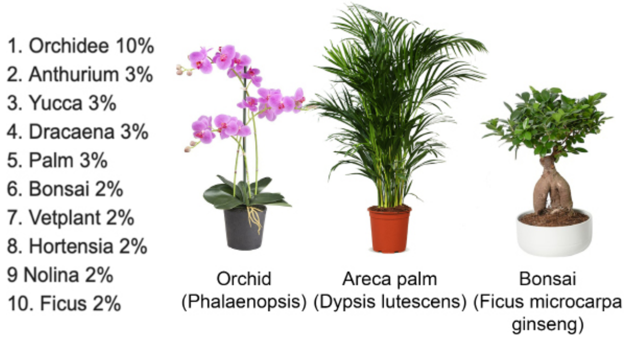


Fig. 81. Dutch indoor plants top 10 (Variavoer.com)

7.6.1 Outer pot

The outer pot has as function to be aesthetically pleasing. This is an important reason for someone to purchase it. By changing the parameters, users can design their own pot which fits perfectly in their home or have a visual match with the plant. However, the outer pot can be made plant-specific as well. For example, the Areca palm needs a big outer pot, in which oxygen is able to reach the lower roots. Oxygen holes will, therefore, be integrated. Another example is the Orchid Phalaenopsis, which needs both oxygen and indirect sunlight on the roots (Croixchatelain.com). By making the 'rings' bigger (see figure 83), indirect sunlight is able to get to the roots. In nature (South-east Asia, Australia, New-Guinea), orchids grow on trees or rocks where their roots can breathe and get sunlight, as shown in figure 82.

Fig. 82. Orchid Phalaenopsis in the rainforest (Pinterest).

When putting this plant in a pot, it still needs oxygen and light on the roots, just like it does when grown in nature. Therefore, special Orchid soil, and a pot that lets through oxygen and light, is required. Although the inner pot is often made from transparent plastic, it regularly gets placed in a closed outer pot, which hinders the growth. Bonsai pots require a low outer pot. Because of the low pot, the light and oxygen coming from above is satisfactory for the roots, and no extra needs to be added on the roots from the side. For a plant like the Bonsai, the parameters can be adjusted to create a unique design matching with the plant, as shown in figure 89. The 3 outer pots are shown in figure 83.

Fig. 83. Parametric design outer pot

Parameters:

Height, width, shell thickness, number of rings per circle, size of rings, shell thickness of rings, vertical distance between rings.

7.6.2 Inner pot

7.6.2.1 Nutrition

The inner pot has multiple functionalities. After watering the plants (for multiple times), the non-crosslinked inner pot slowly dissolves, and eventually, the plant has more space to grow. This makes repotting unnecessary. When dissolving, the nutrition from the calcium carbonate and sodium alginate helps the plant to grow. Calcium carbonate optimizes the PH of soil, prevents plant poisoning, improves the soil structure and the intake of nutrients (Jones., 2012). The calcium from calcium carbonate is good plant nutrition, and sodium alginate has a positive effect on plant growth as well (Khan, 2009). When needed, extra plant-specific nutrients can be processed in the dissolving pot.

When taking a look at the plants discussed earlier, the Phalaenopsis needs airy soil. Such soils, unfortunately, contain hardly any nutrition. Therefore the thickness and contact surface of the inner pot is increased to increase nutrition. Furthermore, the Phalaenopsis grows even better with specific 'Orchid nutrition' (Repotme.com). This orchid nutrition is an 'NPK solution' (nitrogen, phosphorus, potassium), which can be mixed with the paste before 3D printing, as will be shown in chapter 8.

The bonsai needs added Pokon (which is an NPK solution as well) fertilizer (Bonsaiempire.com). The Areca palm does not need extra nutrition. It needs a little 'weak fertilizer', for which the calcium carbonate is sufficient (VanZile, 2020).

7.6.2.2 Dimensions

A plant has to be repotted to prevent rootbound (too many roots). When this happens the soil can not hold the water and the plant dies (houseplantsexpert.com). Starting in a pot that is too big, on the other hand, is bad for a plant as well, because too much energy is going to the growth of the root system, and not to the flowering. When repotting, the plant gets more space, new nutrition, and oxygen (houseplantsexpert.com). Since this pot fulfills all these functionalities, repotting is unnecessary. This also means the user does not have to buy new plant pots, which matches a CE.

Not every plant grows the same, and for that reason, length to width ratio of a pot should not be the same either. The Bonsai, for example, has horizontally growing roots, because it is cultivated to do so. People are fascinated by the art of Bonsai because it looks like a miniature tree, which is separated from its ground fixation, and now continues to live in a pot. To enhance this illusion, low and wide pots are used. The rule of thumb for a bonsai pot is a pot width that equals 2/3th of the plant's height. The pot height should be the same as the root surface (Bonsaiempire.com). Because they are low, bonsai pots lose water quickly. Therefore, the walls and bottom will be made relatively thick, to slow down evaporation, as shown in figure 82. Furthermore, users want to keep their bonsai trees small, which is the illusion of a bonsai. Therefore the inner pot fits perfectly inside the outer pot; no extra space means hardly any extra growth. Since bonsai trees have had years of training to let their roots adapt to small pots, they will not get rootbound and will not die (as discussed before) (Bonsaiempire.com).

On the other hand, roots from the Orchid Phalaenopsis are growing straight to the bottom (Repotme.com), which is why a tall pot is required. For a phalaenopsis extra space is required after 2 to 3 years after purchase. When repotting this plant, an outer pot which is 20% bigger is most desired. (Repotme.com), which is why the outer pot is 20% bigger than the inner pot.

The Areca palm desires a high and wide pot since it is a big plant. On average, a young Areca needs a pot diameter of at least 20 cm (Groenrijk.nl).

7.6.2.3 Light and oxygen

As only a few people know, plants need oxygen. During daytime plants perform photosynthesis; combine CO2, water, and sunlight, and convert it to carbohydrates (glucose (=sugar)) and oxygen. During the nighttime, however, when there is no sunlight, they respire. Respiration is the opposite reaction; they take oxygen and sugar and give off CO2, energy, and water, just like animals do. This released energy is needed to keep the plant alive because during the night it can not take energy from the sun. This process is shown in figure 84 (student-baba.com). Furthermore, enough oxygen in the soil improves water and nutrient intake, which improves the growth and strengthens the root system.

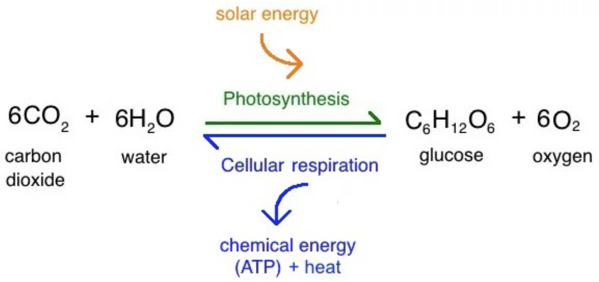


Fig. 84. Photosynthesis & respiration (student-baba.com)

Most plants take carbon dioxide and oxygen in with their leaves, but the Orchid Phalaenopsis, as explained in 7.6.1 breathes mainly with its roots. This is shown schematically in the figure below (85).

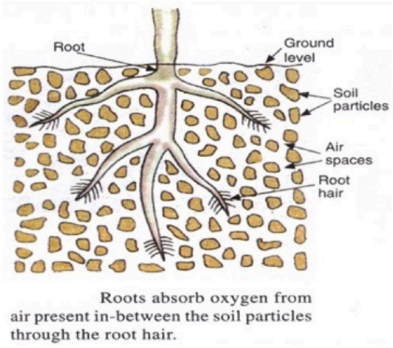


Fig. 85. Plant roots need oxygen (Jagranjosh.com)

To optimize this process both the inner and outer pot will be given breathing holes in the walls. Since this orchid needs illumination on its roots as well (Repotme.com), these holes can also bring some light to the roots. Figure 87 shows these holes. Since the paste printer can not stop with extruding for a short period of time, another way of creating holes was designed. When printing, the rings will bend down which gives a unique 'material-extrusion look' (figure 86).

Fig. 86. Unique material extrusion design.

The Areca palm needs less oxygen and no illumination on the roots (VanZile, 2020), therefore smaller oxygen holes are made (the light does not have to come through). The bonsai does not need extra oxygen or light on the roots (Bonsaiempire.com), which is why the rings will only have a decorative function. For the inner pot, this is not necessary. The soil used for the Areca plant has smaller particles than the Phalaenopsis soil, which is why a pot with bigger holes (like the Phalaenopsis has) would not be suitable.

Fig. 87. Parametric design inner pot

Parameters:
Height, width, shell thickness, number of rings per circle, size of rings, shell thickness of rings, vertical distance between rings.

When comparing the inner pot (figure 87) with outer pot (figure 83), it is remarkable how similar these designs are. This is because inner pot and outer pot parameters (like dimensions, ring size) are adapted on the same plant, and therefore they have almost similar looks. This has the additional benefit that there only needs to be one parametric design for both the inner and outer pot.

7.6.3 Watering funnels

As discussed, the number 1 reason why a plant dies is because of overwatering. Because of overwatering the roots get no oxygen, the roots will rot and finally the plant dies (VanZile, 2020). The material from the planters makes drainage holes unnecessary; the water that is not absorbed by the soil gets slowly absorbed by the outer pot and evaporated from the outside. Drainage, however, should not be necessary at all when the right amount of water is given. For that reason, the 3 plants will be equipped with a parametric designed water funnel. The amount of water a plant needs depends on many factors, like species of tree, size of the tree, size of the pot, time of year, soil-mixture and climate. For the plants described below, the amount of water is based on a dutch climate. The species, tree size, pot size, and soil mixture are known for these plants and were taken into account.

The Areca Palm needs a big amount of water (VanZile, 2020). In garden centers, they are given 500ml twice a week (Groenrijk.nl). This big amount of water is needed because the Areca evaporates a lot of water. The left funnel shown in figure 88 has a capacity of 1L, which needs to be refilled weekly. For people who often forget to water their plants, bigger funnels are possible.

The bonsai tree does not need that amount of water. Because of the low pot, the funnel needs other dimensions, as shown in figure 88. A Ficus Bonsai needs about 100 ml water per week (mynewplant.com). The 100ml funnel needs to be refilled weekly.

The Phalaenopsis does not need much water either. A phalaenopsis in a 3.5-inch pot only needs 3.5 oz (100 ml) of water per week (orchidsuse.com). The 100 ml funnel needs to be refilled weekly.
During winter all the plants require a little bit less water. During this period the excess water is evaporated through the inner and outer pots to prevent waterlogging (drowning the plant).

Since it will be nearly impossible to use this paste to create the perfect watering hole size, the speed water is given to the plant has not been calculated.
To make sure plants still get the right amount of needed water, the funnel size is adapted to the amount of water the plants needs per week. This meand the only thing the user has to do is fill the funnels weekly.

Fig. 88. Parametric design watering funnels

Parameters: *Height, width, volume, size of the watering hole.*

7.7 Experiential characterisation

This concept can be seen as the final result of the experiential characterisation, since the ideation phase was based on the outcomes of the toolkit. But on which areas does the concept still match with the material experience?

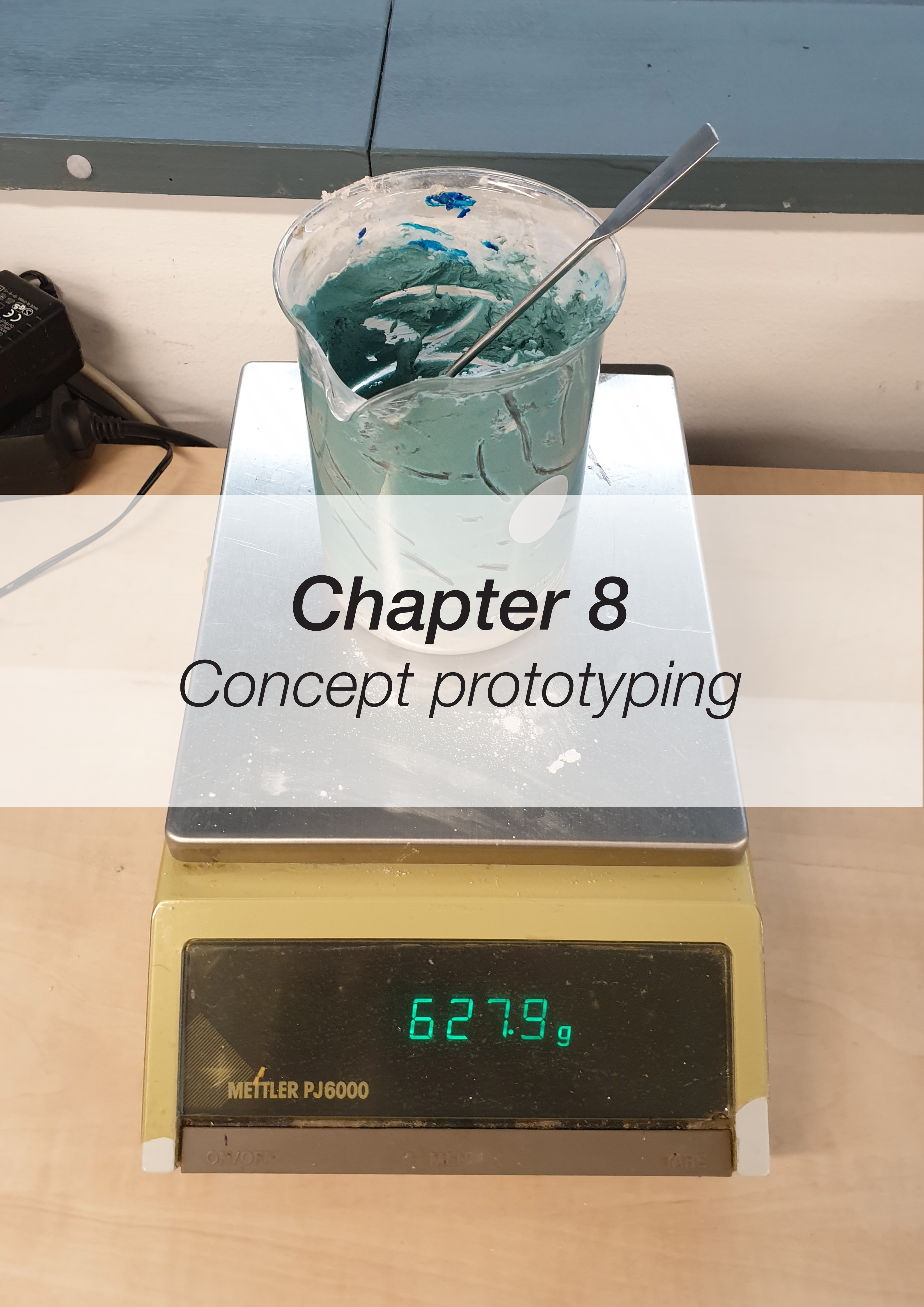
The material had a hand-crafted and ceramic feel, which matches the pottery-like outer pot very well. The warmth and smoothness of the material match the coziness of a living room where these flower pots will be placed. Furthermore, the natural association the material gives matches with plants and flowers.

The most mentioned flaw was the weakness (brittleness) of the material. Other ceramic flower pots, however, will have this property as well, which is why users will know they have to treat it carefully.
Another negative aspect participants mentioned was the color and matte finish, which made it look sober which bored some people. These aspects are addressed in the next chapter.

7.8 Conclusion

This chapter shows the process from a chosen concept towards the Solidworks models of 3 plant-specific parametric designs. These 3 designs show why additive manufacturing can play a role in printing plant-specific planters. Prototyping the plant-specific planter for the Phalaenopsis is chosen since the breathing and lighting holes make it the most interesting one for AM. In the other planters, the holes are only for oxygen, or just for design. These holes can be seen as design resulting from a function; form follows function.
Furthermore, the 3 chosen plants are some of the best selling houseplants in the Netherlands, which matches one of the wishes; Interaction with many different users. For the Phalaenopsis pot, this means there are many 'Orchid communities' (for example http://www.orchidboard.com/community/) which might spend some money on their Phalaenopsis. There are already 'smart planters' on the market, but since they make use of sensors and electronics they are really expensive. That leaves a gap on the market for this plant-specific parametric design.

Fig. 89. 3 plant specific planters made with same parametric design



Chapter 8

Concept prototyping

8.1 Introduction

The previous chapter describes the choice for prototyping a Phalaenopsis outer pot, inner pot and water funnel. The user, who has barely time, skills, or knowledge to give each plant unique care, only has to fill the funnel once a week. The rest of the care is integrated into the parametrically designed plant-specific planter. This chapter shows the 3D printing process of this plant-specific planter, with its parameters adjusted to the Phalaenopsis Orchid.

8.2 Prototyping outer pot

8.2.1 Colorants

The outer pot is the part that draws most attention from the user, which is why it needs to be aesthetically pleasing. As some test users explained in the experiential characterisation user test (chapter 5), the material had a dull appearance because of the gray color. Therefore experiments with coloring the paste was done with food colorants, in the colors red, yellow and blue. Since the material is gray, the colors yellow and red did not turn out as good as the blue color. The blue color combined with the grey material created cyan (blue-green), as shown in figure 90. This color testing also proved that food colorants mixed well with the paste. Even when printing, as shown in figure 92, the colorant remained homogeneously distributed within the material.

Although printing with 2 different colors (figure 100) had an interesting look as result, mixing these colors after recycling would give a dirty-looking color. For that reason there has been chosen to print with 1 color at the same time. However, when giving the product gradients of the same color (light and dark blue) the recycled color would not become a dirty-looking color. To give the outer pot an extra detail, it had been printed in 2 shades of blue, as shown in figure 92.

For this colorant testing, food colorants from Jumbo were used, since they have strict legislation on which E-numbers they are allowed to use. Unfortunately this blue color is not 100% natural, and it appeared that blue colorant is the most difficult color to produce from natural ingredients. Research (Newsome, 2014) discussed a few ways to create natural blue colorants. From this research, ‘Blue Majik’ will possibly be a good match to combine with the musselshell-alginate material. ‘Blue Majik’ is one of the first biological and chemical free blue colorants. It is made from an extract of Arthrospira platensis (spirulina), which is an algae (Newsome, 2014).

Fig. 90. Testing with blue food colorant

8.2.2 Ring diameter

Apart from the looks, the outer pot fulfills a function as well. When parametrically adjusted to the Phalaenopsis, the outer pot needs breathing and illumination holes, as discussed in the previous chapter. The size of these holes can be parametrically adjusted, but the most suitable size for the Phalaenopsis needed to be tested first. Figure 91 shows different ring diameters. To get as much sunlight as possible, it was preferable to create the biggest holes possible. Because of the flowability of the paste, the rings with a diameter lower than 18mm did (almost) close. The ring with a 28mm diameter created a hole that was too big to support, whereafter the layer on top of that hole came down. The ring with a 24mm diameter created the biggest light and air inlet which did not collapse. Therefore a ring size of 24mm was chosen for the prototype of the outer pot.

Combining all previous test results, resulted in the prototype of the outer pot, as shown in figure 92. It took 600 gram (67% shells, 30% water, 3% alginate), 6 refilling sessions and 2:30 hours to print the outer pot. Section 8.5 explains the cura setting choices to create this print.

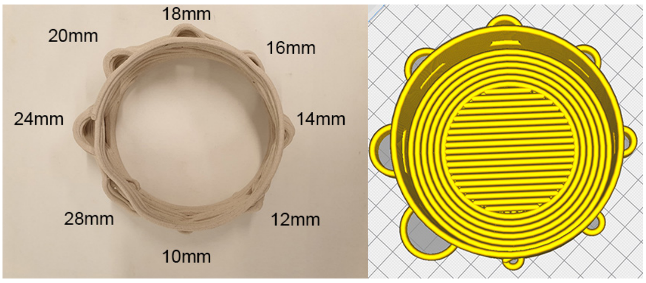


Fig. 91. Testing ring diameter

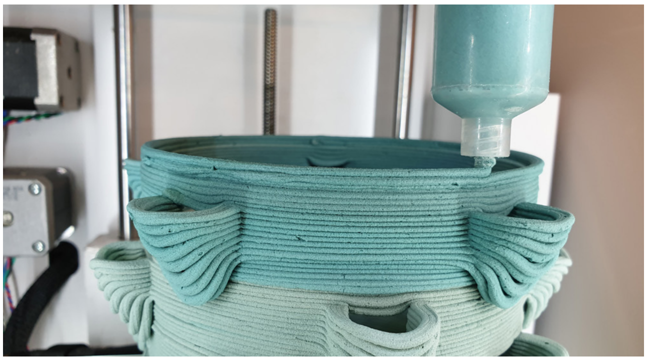


Fig. 92. Printing prototype outer pot

8.3 Prototyping inner pot

8.3.1 Nutrients

The inner pot creates the most unique feature from the concept, since it is the part that slowly dissolves, giving the plant more nutrition and space to keep growing. There are 3 main nutrients in almost all plant plant nutritions; nitrogen (N), phosphorus (P) and potassium (K). For most plants PoKoN would do, but for Orchids there is special Orchid nutrition, in which the ratio of these 3 nutrients is adapted to the Orchids desire. This orchid nutrition can be mixed with the paste, as shown in figure 93. Despite the N, P & K, the sodium alginate became a gel. The used ratio was: 3g sodium alginate, 15g water, and 15g orchid nutrition.

For the inner pot, air and light holes were needed, just like in the outer pot. The holes in the inner pot, however, should be smaller, to make sure the soil particles do not fall out. Because smaller holes also means less light and air gets to the roots, this was compensated by creating more holes. The inner pot has 60 holes, while the outer pot has 30.

Fig. 93. Mixing orchid nutrition with the musselshell paste

Fig. 95. Prototype inner pot

8.3.2 Recycling

Unfortunately, printing the inner pot had another complication. Printing the outer pot took so many material, that the musselshell-powder was almost finished, and it would take to much time to cook, bake and grind new mussel shells. For that reason there was decided to use the recyclability of the paste. All the old prints were broken into pieces, and with a blender grinded into powder. With a sieve the smallest particles were isolated. Since alginate was already integrated in this powder, only water was added. By taking 70g of this powder (3g alginate and 67g shells) and mix it with 30g water, the original paste was created. This process, shown in figure 94, was used to print the entire inner pot, and the funnel. Printing this recycled paste was as easy as printing with the non-recycled paste, and did not give complications because it was recycled. Figure 95 shows the prototype of the printed inner pot.

Fig. 94. Recycling old prints

8.4 Prototyping funnel

8.4.1 Dimensions

The funnels parameters that could be adapted are funnel height, funnel diameter, and diameter of the water outlet. As previous chapter described, a Phalaenopsis needs on average 100 ml water per week, which is why a 100 ml funnel was made which needs weekly refill. Figure 96 describes the calculations for a 100ml cone, made with the google calculation tool for cones. To make sure the funnel does not take over the entire pot, it was preferred to make the biggest diameter max 50% of the diameter of the inner pot. The inner pot has a 100mm diameter, so the desired funnel radius is 25mm. Inserting this in the google tool, resulted in a funnel length of 150mm. About 1/3rd of the funnel will be visible above the ground, so no Phalaenopsis leaves will grow over it. The funnel gets a green color, this color is chosen because it matches with the phalaenopsis leaves, and therefore does not draw that much attention. Furthermore, when (by accident) the funnel and outer pot gets recycled in the same batch, a green-blue color will arise, which is still a good looking color for many products.

8.4.2 Overhang

Since the funnel is the shape of a cone, the maximum overhang had to be tested. The cone shaped print of figure 97 started with printing an angle of 20 degrees. After 11 layers (13mm) this angle appeared to be too big, and the layers collapsed inwards. A possible solution would be to make the walls thicker, but that would leave less space for water, and more material needs to be used. Another solution was to decrease the angle. The same printed object had a 10° overhang in the top (figure 97), which did not give any trouble. When using the dimensions from 8.4.1, an 9.5° angle was calculated, as shown in figure 98. The Inverse Tangent (tan-1) of (25/150)=9.46°. With the result from figure 97 in mind, this overhang should not give trouble. Figure 99 shows the result of the printed funnel.

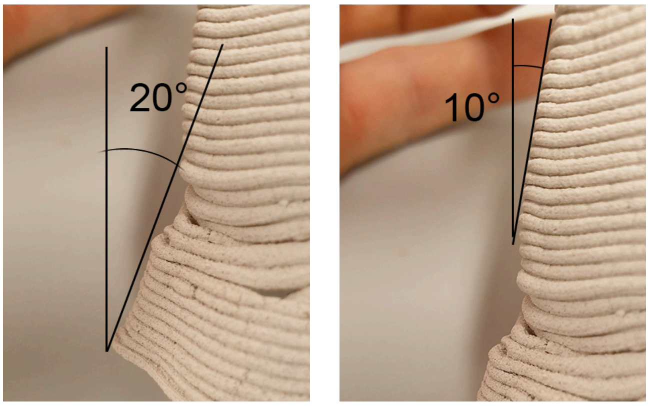


Fig. 97. Testing overhang

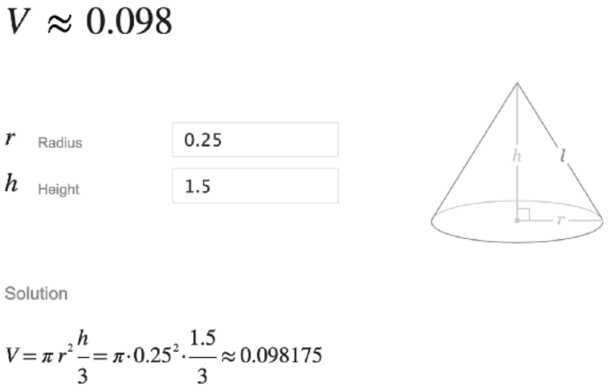
b=25mm
a=150mm
B=arctan(25/150)=9.462322

Fig. 98. Calculate overhang

8.5 Cura settings

8.5.1 Spiralize Outer Contour

As discussed in the previous chapter, the rings and holes were created using a special mode in Cura called 'Spiralize Outer Contour', sometimes called 'vase mode'. These rings were created from a solid block made in Solidworks, and by using 'Spiralize Outer Contour' these rings and walls were created with a single line width (figure 100). Since the outer contour gets spiralized, a steady Z increase over the whole print was created, meaning the Z move is smoothed out, and hardly visible anymore. This special mode was used for all 3 prototypes.



$V \approx 0.098$

r Radius 0.25

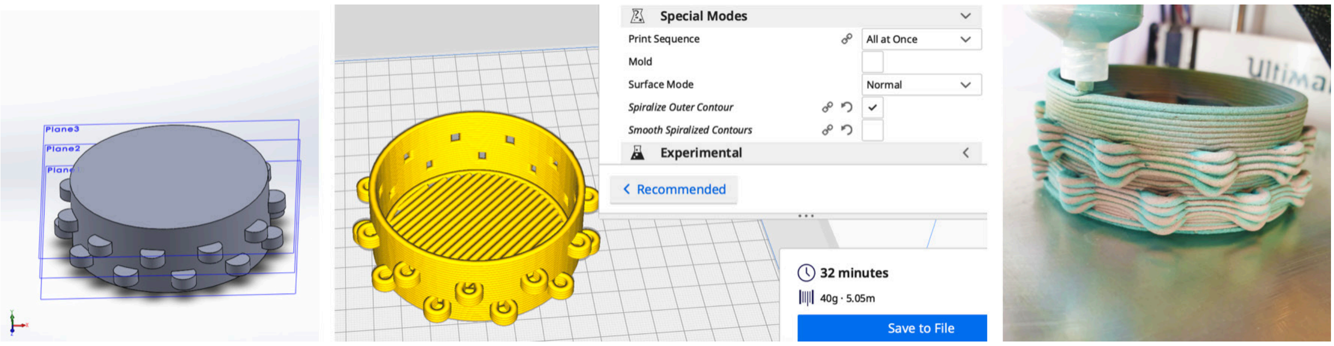
h Height 1.5

Solution

$$V = \pi r^2 \frac{h}{3} = \pi \cdot 0.25^2 \cdot \frac{1.5}{3} \approx 0.098175$$

Fig. 96. Calculating dimensions for a 100ml cone

Fig. 99. Prototype water funnel



Special Modes
Print Sequence: All at Once
Mold: ☐
Surface Mode: Normal
Spiralize Outer Contour: ☑
Smooth Spiralized Contours: ☐
Experimental

Fig. 100. Test creating 'rings' using 'Spiralize Outer Contour'.

8.5.2 General Settings

By using 'Spiralize Outer Contour', the amount of useful Cura settings decreased drastically; there are no differences anymore between inner or outer walls, it does not need infill, nor does it need settings for a shell, etc. The settings that was experimented with, however, are; layer height, line width, bottom layers and print speed

The setting that was most experimented with, was the line width. Until the printing setup changed in chapter 4, a 1.55mm inner diameter nozzle was used (the green nozzle). From chapter 4 till chapter 7 a 2.2mm nozzle was used (the pink nozzle). When bigger prints had to be made, in chapter 7 & 8, the diameter was upgraded to the syringe diameter of 2.5mm. This diameter was later on made wider to 3mm, and finally to 3.5 mm. For the adhesion between lines, the line width was always smaller than the nozzle diameter, so a 3.5mm nozzle printed with a 3mm line width setting in Cura (see figure 101).

This drastic increase in line width was done because other paste printers (clay like van Herpt, or concrete like Malaeb) used very viscous pastes with big nozzles (5mm+) to achieve high prints. Therefore, along with the increase in line width, the amount of water in the paste could be decreased, and higher prints were achieved. The only way this big nozzle size could be achieved was by printing without a nozzle, directly out of the syringe.

The layer height, on the other hand, did not change throughout the project. This caused orange warnings in Cura (figure 101), but had its reasons. By keeping the layer height at 1.2mm, and by increasing the nozzle diameter, walls were created that were thicker than the 3.5mm nozzle (see figure 102), which created a steady base on which even higher prints could be achieved. A second, even more important reason for the low layer height, is the layer adhesion. By making the line width almost 3 times as big as the layer height, the material was forced to spread very well over the previous layer. This improved the layer adhesion, which was needed because the viscous paste (30% water) sometimes had adhesion problems when layers were too dry.

Quality

Layer Height	1.2 mm
Initial Layer Height	1.2 mm
Line Width	3.0 mm

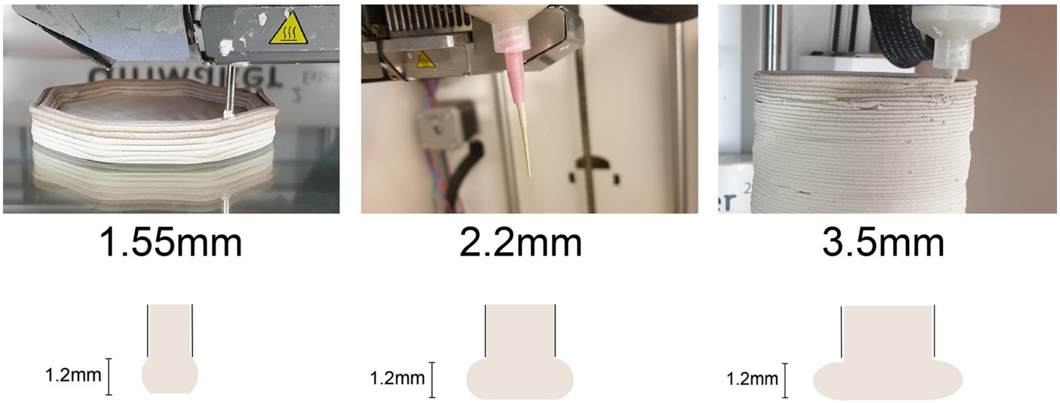
Fig. 101. Layer height and line width warnings

Another cura setting that was changed was the 'bottom layers'. When the extrusion speed was to low, the first layer sometimes had holes. By printing a second bottom layer, the bottoms of the flowerpots did not have holes in it.

The last setting that was experimented with, was the print speed. The inner and outer pot were printed with 5mm/s, which provided enough time to dry the printed object properly to prevent collapsing. The funnel was printed at 3mm/s, since it had a very narrow top. By lowering the print speed, the printed funnel had more time to dry, and had a lower change of collapsing.

The settings used for the prototypes are shown in appendix 9.

Fig. 102. Layer height vs line width



8.6 Discussion

The settings, described in figure 102, made higher prints possible. However, when looking at figure 100, the size of the oxygen and light inlet is smaller in the print than it is in Cura, because the walls are printed thicker than the line width in Cura. This is not so much of a problem when being aware of it, which is why in figure 91 the rings size test was executed; not only to see if the rings would hold, but also to see the rings in a real print instead of seeing it only in Cura.

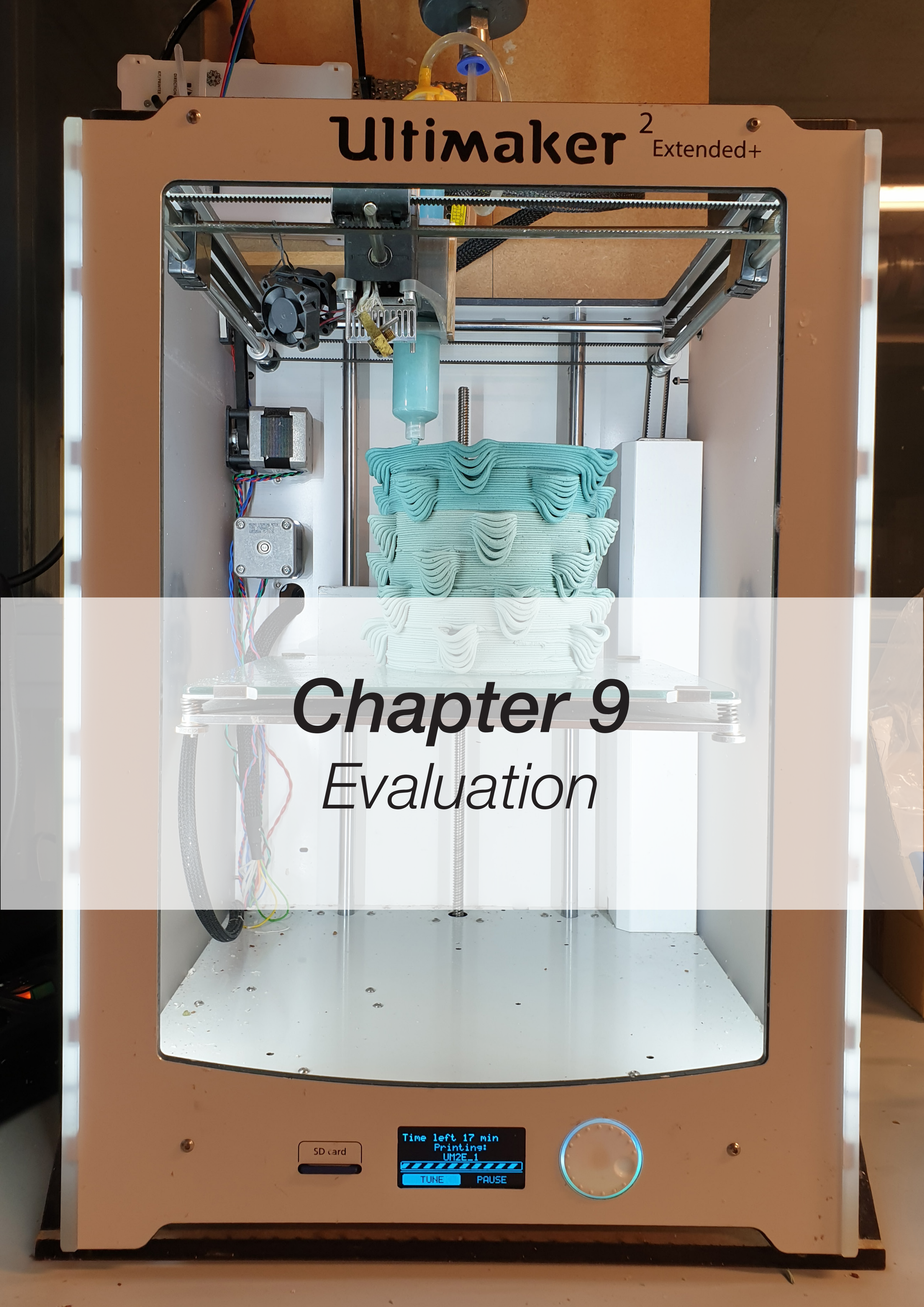
Another disadvantage of this settings, is that a lot of material is needed. However, printing thicker walls was needed to achieve higher prints. Furthermore the thicker walls makes the prints stronger. In that way the weakness of the material is (partly) compensated. The thicker walls might also improve the material experience by the user, since the product feels less fragile. However, to confirm this hypothesis more research need to be done.

Last point of discussion is the multiple-part prototype. The first intention was to design a pot with those 3 prototypes integrated within each other, so only 1 prototype had to be made. When thinking out of a design point of view, this would make a lot of sense. However, when thinking out of a sustainability point of view, it would not. When something breaks in the current prototypes, only 1 of the 3 parts has to be reprinted, instead of everything. This matches with the strategy 'slow loops', which intends to extend a products life. The two parts that are not broken do not have to be reprinted, and in that way their product life is extended.

8.7 Conclusion

By combining all the conclusions and insights from this thesis, it was possible to print the 3 prototypes as planned. The 3 prototypes are shown in figure 103. However, it should be taken into account that these are just prototypes, and that more research and testing needs to be done before these are ready for the market. The future recommendations will be discussed in the next chapter.

Fig. 103. The prototypes



Chapter 9

Evaluation

9.1 Introduction

This final chapter evaluates on the project. Section 9.2 and 9.3 will focus on the evaluation of the parametrically designed planter. Section 9.4 evaluates the project method itself. With the limitations (9.5) found in the project, recommendations (9.6) for the future were formulated. This chapter will wrap up with a personal reflection in section 9.7.

9.2 Main- and sub questions

As discussed in section 1.1, the goal of this thesis was "to design and create a 3D printed product with mussel shell-alginate paste that fits into a circular economy". To get to this goal, 2 main questions, each with 3 sub questions, were formed. The main questions were answered by answering the sub questions throughout the project. This section gives an overview of the answers on these questions.

1. What are the printing properties and material experiences of the mussel shell-sodium alginate paste, and how can we optimize them?

1.1. Is the paste printable (does it extrude) and stable (does it collapse)?

As shown in chapter 4, the original paste (with 40% water) extruded very well, but collapsed when higher prints were made.

1.2. How is the material experienced?

The most important words that were used to describe the material experience (chapter 5) were; natural, hand-crafted, lightweight, soft & warm touch, weak (brittle) and dull color.

1.3. What can we change to optimize these printing properties (printability and stability) and material experience?

The printer setup was changed. Because of the bigger nozzle and short 'paste travel distance', the resistance in the system was decreased, which made printing with a paste with only 27% water possible. This paste did not collapse and prints over 100mm were created.

The material experience was changed by giving the outer pot an attractive color (blue instead of grey), and by printing thick walls the product might feel stronger. Unfortunately, there was no time left to validate this with the user.

2. How can this biobased material be used for suitable and meaningful applications in a CE?

2.1. How to use the experiential characterisation conclusions to get to meaningful applications?

The experiential characterisation conclusions were used as input for individual and group brainstorms (chapter 6). From these +/- 40 ideas, methods were used to bring this to 3 meaningful concepts.

2.2. What strategies can be used so that these applications also suit a CE?

To determine and improve the the match between the concepts and a circular economy, 4 strategies were used; Narrow loops, Slow loops, Close loops, and Regenerate loops (described in chapter 2). Because the material can be recycled, they all match the 'Close loops' strategy. The other 3 strategies differ per concept. It would be ideal when a product matches with all 4 strategies.

The 'parametrically designed plant specific planter also matches with 'slow loops' (as discussed in 8.6), 'Narrow loops' (as discussed in 6.8.1) and 'Regenerate loops' (as discussed in 9.3). The strategies are shown in figure 104.

2.3. What other steps have to be taken into account to print this application?

Chapter 8 focussed on multiple aspects to make the print possible, for example; design (form follows function), overhang, Cura settings, dimensions, recycling, and printing with colorants and added nutrients.

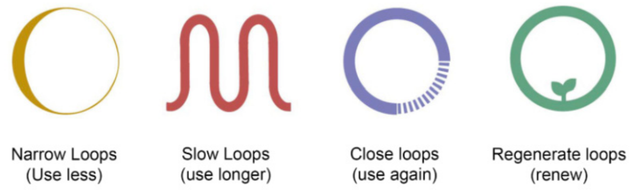
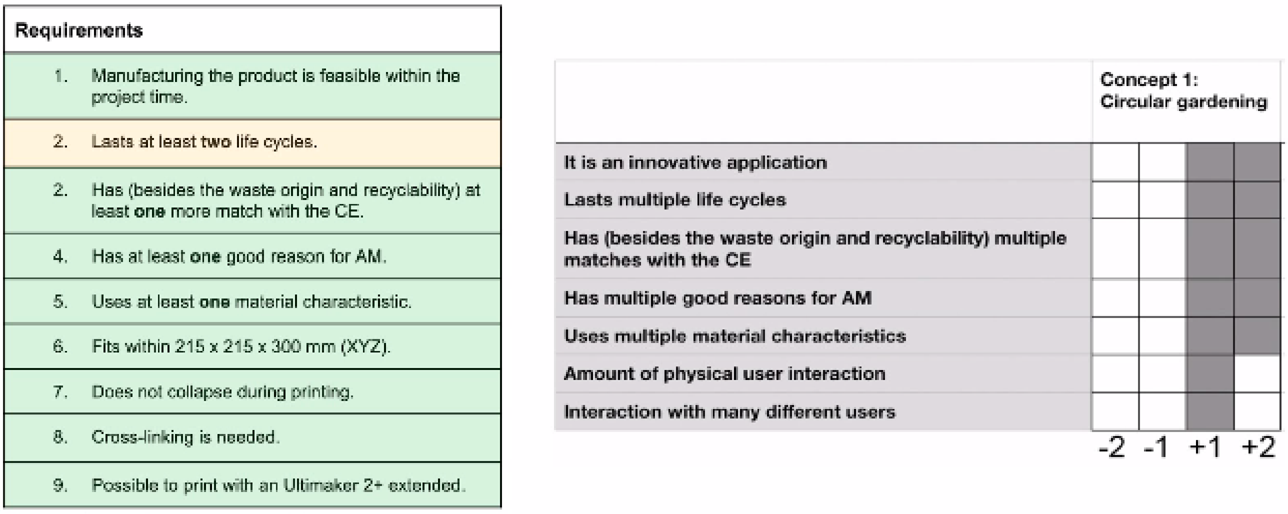


Fig. 104. Circular strategies



Requirements
1. Manufacturing the product is feasible within the project time.
2. Lasts at least two life cycles.
2. Has (besides the waste origin and recyclability) at least **one** more match with the CE.
4. Has at least one good reason for AM.
5. Uses at least **one** material characteristic.
6. Fits within 215 x 215 x 300 mm (XYZ).
7. Does not collapse during printing.
8. Cross-linking is needed.
9. Possible to print with an Ultimaker 2+ extended.

	Concept 1: Circular gardening			
It is an innovative application			▨	▨
Lasts multiple life cycles			▨	▨
Has (besides the waste origin and recyclability) multiple matches with the CE			▨	▨
Has multiple good reasons for AM			▨	▨
Uses multiple material characteristics			▨	▨
Amount of physical user interaction			▨	
Interaction with many different users			▨	
	-2	-1	+1	+2

Fig. 105. Requirements and wishes

9.3 Requirements and wishes

In this section the final concept will be evaluated based on the requirements and wishes, which are shown in figure 105. The requirements and wishes were taken into account throughout the whole project.

Requirements

Figure 104 shows that (almost) all requirements have been met, but there was some doubt about the second requirement.

The 3 prototypes were made of 1100 gram paste in total, of which 400 gram for the inner pot. When the inner pot gets absorbed by the plant, 700 gram can still be recycled and have a second life cycle. However, it is a matter of how a 'second life' gets interpreted. Natural ecosystems are seen as a perfect circular system (MacArthur, 2013); when for example a tree or animal dies, its remaining nutrients gets absorbed by the ground to grow new grass or plants (circle of life). This also means, that when the inner pot gets dissolved and absorbed by the plant, it basically gets recycled by nature. This actually means the inner pot gets a second life cycle as well. Since a waste stream is used to regenerate the loop of an ecosystem (plants), this part of the concept matches with the 'Regenerate loops' strategy, as shown in figure 104.

Because of a lack of time, unfortunately, there is no 100% proof that the inner pot gets absorbed by the plant. Therefore, I recommend future testing towards this topic (as shown in section 9.6).

The other 8 requirements are 'green' because they have already been proven throughout the project.

Wishes

The wishes have been discussed in chapter 6. Chapter 7, however, made changes to this concept. By making a 'parametrically designed plant specific planter' the reason for using AM (wish 4) and innovativeness (wish 1) were increased. Therefore, figure 105 shows these wishes were rewarded a '+2', instead of the previous '+1'. The other 5 wishes were not influenced by the changes in chapter 7. Wish 2 has the same issue as described in the 'requirements' section, but when accepting that regenerating the loop of an ecosystem, can be seen as recycling (and a new life) as well, this wish is fulfilled.

9.4 Methodology

Right after the literature phase (chapter 1-3), this thesis started with something the MDD method calls 'tinkering with the material'. This is a kind of explorative research of creation, testing and evaluation which entails a thorough understanding of the material you are going to design with. This chapter revealed a lot of qualities and constraints on which the rest of the thesis is based. Together with the experiential characterisation, the creative sessions and the product conceptualisation, the (for this project) most important MDD parts were highlighted (figure 106). By skipping step 2 & 3, more focus was given to step 1 & 4, which resulted in a lot of outcomes for these steps (for example the experiential characterisation).

As Karana explains in the discussion of the MDD method, the 4 steps are a suggested sequence of steps. The nature of the design project might alter the way these steps are conducted, *'or even might result in omission of one or more steps'* (Karana et al., 2015).

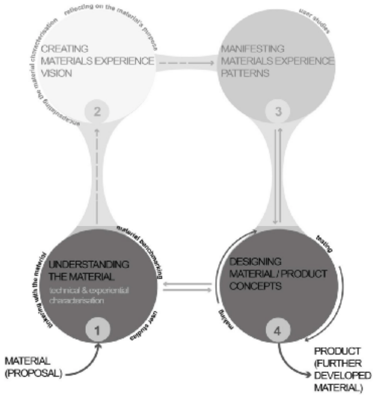


Fig. 106. MDD method

In the experiential characterisation I made use of the Ma2E4 toolkit. This is a very structured and efficient method for the experiential characterisation. As described in chapter 5, 3 questions were added in this toolkit. In my opinion these questions helped to understand the answers from the participants. Since the ideation phase has a role in all the 4 steps (not just the last one), the added question about applications suits the toolkit. It took users 30 minutes to explain how they experienced the material, so most of them have plenty ideas what they would do with the material. And if they have plenty ideas, why not ask them to describe them.

Overall the MDD method was a good guidance for the complete process. The way of working with this method, however, sometimes felt different than I was used to. The IDE bachelor and Master teaches to start designing out of a 'problem', and later on in the conceptualisation phase match this with a suitable material. In this way of working the literature about a certain problem can be covered in the first steps of the project. During this thesis, a clear product direction was chosen after the conceptualisation phase. Because the concepts resulted out of material characteristics, there was not so much background about the problem the product solves. In other words; by using this method a second litterature/knowledge phase started after the concept was chosen. After spending a week in deepening my knowledge in plants, planters, plant nutrition and plant care, the design phase could continue.
Furthermore, methods from the Delft design Guide (Boeijen et al., 2017) were used; brainwriting, brain drawing, C-box and Harris-profile. While during the project decision-making was sometimes not well enough documented, I personally think the decisions in the conceptualisation phase had been improved and decision are logical and understandable.
Finally, this thesis used 4 circular strategies (figure 103) which helped to match the concepts with the circular economy in multiple ways. These strategies also helped to make logical choices in the harris profile, for the 'match with a CE' wish.

9.5 Limitations

Throughout the project multiple material limitations were discussed. In this evaluation the most important limitations of this biobased material will be mentioned.

Material strength
The first, and most important limitation, is the material's strength. Because +/- 95% of the dried paste consists of calcium carbonate (CaCo3), the properties are almost the same as well. This means that the paste is very brittle, and this weakness is perceived by the user as well (chapter 5). This limitation can partially be compensated by making thick-walled prints.

Printing limitations
The second, third and fourth limitation has to do with the printing properties. Because it is a paste it dries (instead of solidifying). Dependant on the viscosity, temperature and thickness the drying time can easily exceed 24 hours.
Because of this slow drying time, it is needed to create a very viscous paste, otherwise high prints will collapse. However, when doing this, the layer adhesion is influenced because pastes need moist layers for good layer adhesion. This means a concession needs to be made between print height and layer adhesion. In this thesis that concession was set at a paste with 30% water. Furthermore, the paste 'flows', and can not make sharp corners. For that reason the paste is not suited for products that require details (detailed spare parts etc). When designing, this has to be taken into account; angles or rough details needs to be magnified in solidworks, to make them visible in the final print.

Production & recycling speed
Another limitation is the powder production and recyclability. The most unique part of the material is that it is formed out of a waste stream, and can be recycled without perceiving quality loss (figure 94). The time this requires to do by hand, however, is that long that it might be a reason for people to search for a completely different material. These 5 limitations are displayed in figure 107.

1. The material is very brittle
2. The paste has a long drying time
3. A concession between print height and layer adhesion is needed
4. Paste is unable the print sharp corners and details
5. Creating mussel powder and recycling old prints takes a lot of time

Fig. 107. Most important material limitations

9.6 Recommendations

Based on the limitations described above, and other insights gathered in this project, some recommendations for future development were made.

Improve material weakness & improve production speed

The first recommendation would be to continue with the material development research. The material is still brittle, and when this can be overcome, one of the biggest material limitations is improved. A possible reason why the material is very brittle, is because it is made from brittle shells. The mussel-shells are made brittle (by putting them in the oven) to make it easier to grind. However, when a more powerful grinder can be used, the shells do not have to be made brittle, which might improve the technical material characteristics.

With a more powerful (and bigger) grinder, the production time of the musselshell-powder (and recycling time) might be decreased as well, which is one of the 5 limitations described above.

Kaumera

Furthermore, as discussed in section 2.3.2, sodium alginate does not perfectly match a circular economy, because acids are used in the production process which are discarded afterwards. Recently, however, a new alginate-like material called Kaumera, can be sourced from sewage (Verdonk, 2019). This material fits a CE and can in the future possibly replace the sodium alginate since it has (almost) the same properties as alginate. Therefore it is recommended to test with this material when it is available

Calcium carbonate sources

There are many sources of calcium carbonates, so if this paste can be made with other CaCo3 waste streams as well (other shells, bones from the meat industry), multiple waste streams can be diminished. It is also an advantage when the system does not have to depend on one single material source.

Cross linking

Right now the 3d print gets crosslinked after the print is made. However, since crosslinking has a positive effect on the material properties, crosslinking before printing (crosslink the paste), or during printing (figure 16, Tabriz et al., 2015), might be possibilities as well. This might have a positive effect on printing process.

User validation

Although the final concept is based on user tests (experiential characterisation), there was not enough time to use the prototype for validation with the users. How is the blue color perceived? Do the thick walls still feel weak? Those kind of questions should be validated.

Test with plants

The prototype should be validated with the plant as well. Since the inner pot dissolves really slowly, and a Phalaenopsis grows really slowly, this could not be tested within this project. Although small tests showed it should be working, the actual dissolving of an entire inner pot had not yet been tested. This should be one of the first step when continuing with this concept; the parametrically designed plant specific planter.

Test strength after recycling

The recyclability of the is (one of) the most interesting properties of the developed material. Section 8.3.2. showed that recycling the paste does not give troubles for printing, but does this also mean it is as strong as the 'virgin material'? Previous research showed that similar material (paste with sugarwater) resulted in an equivalent material after recycling. However, because of the low sample size, the results are indicative. Therefore, more testing (and testing with the mussel-alginate paste) should be done.

The figure below shows the 8 recommendations in an overview.

1. Test with Improving the materials strength.
2. Research how to increase the production and recycling speed of the material.
3. Test Kaumera as a binder.
4. Test other sources of CaCo3 as filler.
5. Test cross-linking in an earlier stage.
6. Validate the prototype with the users.
7. Validate the prototype with plants.
8. Test strength after recycling.

Fig. 108. Recommendations

9.7 Personal reflection

At the start of this thesis, I was assuming that a thesis is a project in which all the skills and knowledge gained during the bachelor and master would be combined. It did not take long before I realised that was not entirely the case. In a thesis some skills are needed, that are not taught during IDE bachelor or masters. This means you need time to learn those skills, and then make them your own. For me, the biggest gap in knowledge was primarily during the first 3 chapters; the literature research. Academically writing, referencing sources, and taking credits for your own insights, were skills that took months of improvement. Eventually I think it has improved to a thesis-worthy level.

The other chapters (mainly 4, 5 and 8) progressed much smoother, since creating prototypes and doing user research are skills I have developed during my bachelor and master, and have my personal interest.

As a product designer, I really enjoyed this thesis which is a combination between optimizing a sustainable material, designing something new, and 3D printing. I am happy that I can conclude this thesis with a design that matches both the material, the circular economy and additive manufacturing. I think the story and documentation is coherent and complete enough to serve as input for future projects and research on this topic. As described in the personal project brief (Appendix 1), it was my ambition to increase my knowledge about a circular economy, and my material testing skills, which have been used and improved a lot throughout the project. After all this material testing and improvement, I personally think that there lies way more potential in this sustainable material than I was able to show in 20 weeks. With more research (see recommendations) the material can be exploited further to create more applications. Therefore, I truly hope that there will be continuity with this material.

As a final word I would like to thank Zjenja and Mariet for their supervision and guidance throughout this project. The meetings, once every two weeks, kept me on track and created structure in the project. I am content with the feedback I received during the meetings.

Sources

3D printers for ceramics, concrete and pastes, extruders and print heads. (n.d.). Retrieved October 20, 2019, from https://www.stoneflower3d.com/.

3D PRINTTECHNIEKEN. (n.d.). Retrieved October 18, 2019, from https://deminifabriek.nl/3d-printtechnieken/.

Algaia alginates • Algaia. (n.d.). Retrieved October 24, 2019, from https://www.algaia.com/.

alginate. (n.d.). Retrieved October 24, 2019, from http://www.fao.org/3/y4765e/y4765e08.htm.

Axpe, E., & Oyen, M. L. (2016). Applications of alginate-based bioinks in 3D bioprinting. International journal of molecular sciences, 17(12), 1976.

Badwan, A. A., Abumalooh, A., Sallam, E., Abukalaf, A., & Jawan, O. (1985). A sustained release drug delivery system using calcium alginate beads. Drug Development and Industrial Pharmacy, 11(2-3), 239-256.

Bakarich, S. E., Gorkin III, R., Panhuis, M. I. H., & Spinks, G. M. (2015). 4D printing with mechanically robust, thermally actuating hydrogels. Macromolecular rapid communications, 36(12), 1211-1217.

Bakker, C., & Mugge, R. (2017). Sauerwein et al. M., Bakker CA and Balkenende AR. Delft University of Technology, 8, 10.

Bakker, C. (2019). Products that last: product design for circular business models. London: BIS Publishers.

Bao, W., Zhang, Z., Gan, Y., Wang, X., & Lia, J. (2013). Enhanced cyclability of sulfur cathodes in lithium-sulfur batteries with Na-alginate as a binder. Journal of Energy Chemistry, 22(5), 790-794.

Barros, M. C., Bello, P., Bao, M., & Torrado, J. J. (2008). From Waste to Commodity: Transforming Shells into High Purity Calcium Carbonate. Journal of Cleaner Production, 400-407.

Bengisu, M. (2013). Engineering ceramics. Springer Science & Business Media.

Bocken, N. M. P., De Pauw, I., Bakker, C., & Van Der Grinten, B. (2016). Product design and business model strategies for a circular economy. Journal of Industrial and Production Engineering ISSN:, 33(5), 308–320. https://doi.org/10.1080/21681015.2016.1172124

Boeijen, A. van, Daalhuizen, J., Zijlstra, J., Schoor-Rombouts, R. van der., Zijlstra, Y., & Kuntonen, J. (2017). Delft design guide: design methods, Delft University of Technoloy, faculty of industrial design engineering. Amsterdam: BIS Publishers.

Bose, S., Vahabzadeh, S., & Bandyopadhyay, A. (2013). Bone tissue engineering using 3D printing. Materials today, 16(12), 496-504.

Chapman, J. (2014). Meaningful stuff: Toward longer lasting products. In Materials Experience (pp. 135-143). Butterworth-Heinemann.

Chef, Q. (2014, August 6). Sodium Alginate (alginate, algin). Retrieved October 24, 2019, from http://www.molecularrecipes.com/hydrocolloid-guide/sodium-alginate-alginate-algin/.

Chen, D., Heyer, S., Ibbotson, S., Salonitis, K., Steingrimsson, J. G., & Thiede, S. (2015). Direct digital manufacturing: definition, evolution, and sustainability implications. Journal of Cleaner Production, 107, 615–625.

Chen, X., Possel, J. K., Wacongne, C., Van Ham, A. F., Klink, P. C., & Roelfsema, P. R. (2017). 3D printing and modelling of customized implants and surgical guides for non-human primates. Journal of neuroscience methods, 286, 38-55.

Chen, Z., Li, Z., Li, J., Liu, C., Liu, C., Li, Y., ... & Yuelong, F. (2018). 3D printing of ceramics: a review. Journal of the European Ceramic Society..

Chia, H. N., & Wu, B. M. (2015). Recent advances in 3D printing of biomaterials. Journal of biological engineering, 9(1), 4.

Concurrentiestrijd in mosselland: de échte Zeeuwse mossel staat op (2017) (accessed 14.10.19), https://www.omroepzeeland.nl/nieuws/99385/Concurrentiestrijd-in-mosselland-de-echte-Zeeuwse-mossel-staat-o

Complete lijst waterhardheden Nederland. (n.d.). Retrieved February 17, 2020, from https://www.waterhardheid.nl/lijst-waterhardheden-in-nederland

Crushed shells and 3D printing (2018) (accessed 14.10.19), https://webgate.ec.europa.eu/fpfis/cms/farnet2/on-the-ground/good-practice/short-stories/crushed-shells-and-3d-printing_en

Dehn, J. (2014). Conception and realization of a sustainable materials library. In Materials Experience (pp. 155-168). Butterworth-Heinemann.

Delaney, J. T., Liberski, A. R., Perelaer, J., & Schubert, U. S. (2010). Reactive inkjet printing of calcium alginate hydrogel porogens—a new strategy to open-pore structured matrices with controlled geometry. Soft Matter, 6(5), 866-869.

Despeisse, M., Baumers, M., Brown, P., Charnley, F., Ford, S., Garmulewicz, A., ... Rowlye, J. (2017). Unlocking value for a circular economy through 3D printing: a research agenda. Technological Forecasting and Social Change, 115, 75–84.

Devina, N., Eriwati, Y. K., & Santosa, A. S. (2018). The purity and viscosity of sodium alginate extracted from Sargassum brown seaweed species as a basic ingredient in dental alginate impression material. Journal of Physics: Conference Series, 1073, 052012. doi: 10.1088/1742-6596/1073/5/052012

Dick, A., Bhandari, B., & Prakash, S. (2019). 3D printing of meat. Meat science.

Durão, L. F. C., Christ, A., Anderl, R., Schützer, K., & Zancul, E. (2016). Distributed manufacturing of spare parts based on additive manufacturing: use cases and technical aspects. Procedia CIRP, 57, 704-709

Engineering Cartoon - Unlimited Download. cleanpng.com. (n.d.). Retrieved December 9, 2019, from https://www.cleanpng.com/png-hydraulic-drive-system-hydraulics-hydraulic-machin-5538306/download-png.html.

Esmaeilian, B., Behdad, S., & Wang, B. (2016). The evolution and future of manufacturing: A review. Journal of Manufacturing Systems, 39, 79–100. https://doi.org/10.13140/RG.2.1.2720.0402

Exploring Shellfish By-products as sources of Blue Bioactivities (BlueShell) (2017) (accessed 14.10.19), http://www.marinebiotech.eu/blueshell

Ficus bonsai tree. (n.d.). Retrieved February 19, 2020, from https://www.bonsaiempire.com/tree-species/ficus

Fitzer, S. C., Chung, P., Maccherozzi, F., Dhesi, S. S., Kamenos, N.A., Phoenix, V. R., & Cusack, M. (2016). Biomineral shell formation under ocean acidification: a shift from order to chaos. Nature. doi:10.1038/srep21076

Fitzpatrick, A. P., Mohanned, M. I., Collins, P. K., & Gibson, I. (2017). Design of a patient specific, 3D printed arm cast. KnE Engineering, 135-142.

Ford, S., & Despeisse, M. (2016). Additive manufacturing and sustainability: an exploratory study of the advantages and challenges. Journal of Cleaner Production, 137, 1573–1587. https://doi.org/10.1016/j.jclepro.2016.04.150

Frear, G. L., & Johnston, J. (1929). The solubility of calcium carbonate (calcite) in certain aqueous solutions at 25. Journal of the American Chemical Society, 51(7), 2082-2093.

Gebhardt, A. (2011). Understanding additive manufacturing.

Geiser, K. G. K. (2001). Materials matter. Mit Press.

Godoi, F. C., Prakash, S., & Bhandari, B. R. (2016). 3d printing technologies applied for food design: Status and prospects. Journal of Food Engineering, 179, 44-54.

Goldin, M. E. L. I. S. A. (2014). Chinese Company Builds Houses Quickly With 3D Printing. mashable. com, April, 29.

Grootste mosselkwekers uit Nederland en Duitsland bundelen krachten (2019) (accessed 13.10.19), https://www.de-bevelander.nl/nieuws/zakelijk/709215/grootste-mosselkwekers-uit-nederland-en-duitsland-bundelen-krachten

Hager, I., Golonka, A., & Putanowicz, R. (2016). 3D printing of buildings and building components as the future of sustainable construction?. Procedia Engineering, 151, 292-299.

Halada, K., & Yamamoto, R. (2001). The current status of research and development on ecomaterials around the world. MRS bulletin, 26(11), 871-879.

Hamester, M.R.R., Balzer, P.S., Becker, D., Characterization of calcium carbonate obtained from oyster and mussel shells and incorporation in polypropylene, Mater. Res. 15 (2012) 204–208, http://dx.doi.org/10.1590/S1516-14392012005000014.

Hart, P. W., Colson, G. W., & Burris, J. (2011). Application of carbon dioxide to reduce water-side lime scale in heat exchangers. J Sci Technol For Prod Process, 1, 67-70.

Hay, I. D., Rehman, Z. U., Moradali, M. F., Wang, Y., & Rehm, B. H. A. (2013). Microbial alginate production, modification and its applications. Microbial Biotechnology. doi: 10.1111/1751-7915.12076

Herpt, O. van. (n.d.). Functional 3D Printed Ceramics. Retrieved October 20, 2019, from http://oliviervanherpt.com/functional-3d-printed-ceramics/.

Het Nederlands Mosselbureau, Achtergrondinformatie-persdossier mosselen (2014) http://www.mosselbureau.nl/pers/persdossier.htm (accessed 07.10.19).

Horne, F. (2006). How are seashells created? Or any other shell, such as a snail's or a turtle's? Opgehaald van Scientific America: https://www.scientificamerican.com/article/ how-are-seashells-created/

Huang, S.-C., Naka, K., & Chujo, a. (2007). A Carbonate Controlled-Addition Method for Amorphous Calcium Carbonate Spheres Stabilized by Poly(acrylic acid)s. 23(24), 12086-12095. doi:10.1021/la701972n

Huang, Y., Leu, M. C., Mazumder, J., & Donmez, A. (2015). Additive Manufacturing: Current State, Future Potential, Gaps and Needs, and Recommendations. Journal of Manufacturing Science and Engineering, 137(1), 14001. https://doi.org/10.1115/1.4028725

Hurcombe, L. (2007). A sense of materials and sensory perception in concepts of materiality. World Archaeology, 39(4), 532-545.

Israel, G. D. (1992). Determining sample size.

Jones Jr, J. B. (2012). Plant nutrition and soil fertility manual. CRC press.

Karana, E., Barati, B., Rognoli, V., Der Laan, V., & Zeeuw, A. (2015). Material driven design (MDD): A method to design for material experiences.

Karana, E., Hekkert, P., & Kandachar, P. (2009). Meanings of materials through sensorial properties and manufacturing processes. Materials & Design, 30(7), 2778-2784.

Karana, E. (2010). How do materials obtain their meanings?. METU Journal of the Faculty of Architecture, 27(2).

Karana, E. (2012). Characterization of 'natural'and 'high-quality'materials to improve perception of bio-plastics. Journal of Cleaner Production, 37, 316-325.

Kato, T. (2000). Polymer/Calcium Carbonate Layered Thin-Film Composites. Advanced Materials, 12(20).

Khan, W., Rayirath, U. P., Subramanian, S., Jithesh, M. N., Rayorath, P., Hodges, D. M., ... & Prithiviraj, B. (2009). Seaweed extracts as biostimulants of plant growth and development. Journal of Plant Growth Regulation, 28(4), 386-399.

Kilan, K., & Warszyński, P. (2014). Thickness and permeability of multilayers containing alginate cross-linked by calcium ions. Electrochimica Acta, 144, 254-262.

Kira, Exclusive: WinSun China builds world's first 3D printed villa and tallest 3D printed apartment building, 3D Printer and 3D Printing News, 2015.

Knight, B. (2019, November 9). After being fished to near-extinction last century, Australia's lost shellfish reefs are roaring back to life. Retrieved October 17, 2019, from https://www.abc.net.au/news/2019-11-09/project-brings-near-dead-reefs-back-to-life-across-australia/11681904.

Knill, C. J., Kennedy, J. F., Mistry, J., Miraftab, M., Smart, G., Groocock, M. R., & Williams, H. J. (2004). Alginate fibres modified with unhydrolysed and hydrolysed chitosans for wound dressings. Carbohydrate Polymers, 55(1), 65-76.

Kohtala, C. (2015). Addressing sustainability in research on distributed production: an integrated literature review. Journal of Cleaner Production, 106, 654–668.

KORENBLIT, M. (2019, January 18). Crushed shells and 3D printing - FARNET. Retrieved October 17, 2019, from https://webgate.ec.europa.eu/fpfis/cms/farnet2/sites/farnet/files/06-from-crushed-shells-to-3d-printing-it.pdf

Lin, Y. H., Liang, H. F., Chung, C. K., Chen, M. C., & Sung, H. W. (2005). Physically crosslinked alginate/N, O-carboxymethyl chitosan hydrogels with calcium for oral delivery of protein drugs. Biomaterials, 26(14), 2105-2113.

Ljungberg, L. Y. (2007). Materials selection and design for development of sustainable products. Materials & Design, 28(2), 466-479.

MacArthur, E. (2013). Towards the circular economy. Journal of Industrial Ecology, 2, 23-44.

Malaeb, Z., Hachem, H., Tourbah, A., Maalouf, T., El Zarwi, N., & Hamzeh, F. (2015). 3D concrete printing: machine and mix design. International Journal of Civil Engineering, 6(6), 14-22.

Mani, M., Lyons, K. W., & Gupta, S. K. (2014). Sustainability Characterization for Additive Manufacturing. Journal of Research of the National Institute of Standards and Technology, 119, 419–428.

manufacturer and worldwide supplier of alginate. (n.d.). Retrieved October 19, 2019, from https://kimica-algin.com/alginate/usage/.

manufacturer and worldwide supplier of alginate. (n.d.). Retrieved October 24, 2019, from https://kimica-algin.com/alginate/process/.

Marlborough Express. (2014). Farmer develops mussel shell fertilizer. Opgehaald van MarlboroughExpress.com: http://www.stuff.co.nz/business/farming/agribusiness/9849293/Farmer-develops-mussel-shell- fertiliser

Materials Experience Lab. (n.d.). Retrieved October 29, 2019, from http://materialsexperiencelab.com/.

Matsumoto, M., Yang, S., Martinsen, K., & Kainuma, Y. (2016a). Trends and Research Challenges in Remanufacturing. INTERNATIONAL JOURNAL OF PRECISION ENGINEERING AND MANUFACTURING-GREEN TECHNOLOGY, 3(1), 129–142. https://doi.org/10.1007/s40684-016- 0016-4

McHugh, D. J. (1987). Production, properties and uses of alginates. Production and Utilization of Products from Commercial Seaweeds. F\ AO. Fish. Tech. Pap, 288, 58-115.

McHugh, Dennis J. "A Guide to the Seaweed Industry, FAO Fisheries Technical Paper 441." Food and Agriculture Organization of the United Nations, 2003.

Milieu Centraal, Groente, fruit en tuinafval (gft), (2016) (accessed 07.10.19), https://www.milieucentraal.nl/minder-afval/afval-scheiden-en-recyclen/welk-afval-waar/groente-fruit-en-tuinafval-gft/.

Nederlandse mosselveiling (2019) (accessed 13.10.19), https://www.mosselen.nl/nl/mosselinfo/nederlandse-mosselveiling/

Newsome, A. G., Culver, C. A., & Van Breemen, R. B. (2014). Nature's palette: the search for natural blue colorants. Journal of agricultural and food chemistry, 62(28), 6498-6511.

Ngo, T. D., Kashani, A., Imbalzano, G., Nguyen, K. T., & Hui, D. (2018). Additive manufacturing (3D printing): A review of materials, methods, applications and challenges. Composites Part B: Engineering, 143, 172-196.

On-demand Manufacturing: Quotes in Seconds, Parts in Days. (n.d.). Retrieved October 20, 2019, from https://www.3dhubs.com/

Over de mossel (2019) (accessed 13.10.19), https://www.mosselen.nl/nl/mosselinfo/over-de-mossel/

Pearce, D. W., & Turner, R. K. (1990). Economics of natural resources and the environment. JHU Press.

Pei, E., Duran, C., Subbian, V., Giovanetti, M. T., Simkins, J. R., & Beyette Jr, F. R. (2015). Experimental desktop 3D printing using dual extrusion and water-soluble polyvinyl alcohol. Rapid Prototyping Journal.

Phalaenopsis Care. (n.d.). Retrieved February 19, 2020, from https://www.repotme.com/pages/phalaenopsis-care

Phalaenopsis orchid: plant and pot in perfect harmony. (2019, January 10). Retrieved February 10, 2020, from https://www.croixchatelain.com/en/orchid-phalaenopsis-plant-and-pot-in-perfect-harmony/

Pignolet, L. H., Waldman, A. S., Schechinger, L., Govindarajoo, G., & Nowick, J. S. (1998). The alginate demonstration: Polymers, food science, and ion exchange. Journal of chemical education, 75(11), 1430.

Popescu, D., Zapciu, A., Tarba, C., & Laptoiu, D. (2019). Fast production of customized three-dimensional-printed hand splints. Rapid Prototyping Journal.

Prendeville, S., Hartung, G., Purvis, E., Brass, C., & Hall, A. (2016). Makespaces: From Redistributed Manufacturing to a Circular Economy. In R. Setchi, R. J. Howlett, Peter Theobald, & Ying Liu (Eds.), Sustainable Design and Manufacturing 2016 (pp. 577–588). Cham: Springer.

Rijksoverheid. (2014). Nationaal Strategisch Plan 2014-2020.

Rodriguez-Navarro, C., Kudłacz, K., Cizerc, Ö., & Ruiz-Agudoa, E. (2015). Formation of amorphous calcium carbonate and its transformation into mesostructured calcite.

Rognoli, V., & Karana, E. (2014). Toward a new materials aesthetic based on imperfection and graceful aging. In Materials Experience (pp. 145-154). Butterworth-Heinemann.

Rognoli, V., Salvia, G., & Levi, M. (2011, June). The aesthetic of interaction with materials for design: the bioplastics' identity. In Proceedings of the 2011 Conference on Designing Pleasurable Products and Interfaces (p. 33). ACM.

Sauerwein et al., M., & Doubrovski, E. L. (2018). Local and recyclable materials for additive manufacturing: 3D printing with mussel shells. Materials Today Communications, 15, 214-217.

Sauerwein et al., M., Doubrovski, E., Balkenende, R., & Bakker, C. (2019). Exploring the potential of additive manufacturing for product design in a circular economy. Journal of Cleaner Production, 226, 1138-1149.

Sauerwein et al., M., Karana, E., & Rognoli, V. (2017). Revived beauty: research into aesthetic appreciation of materials to valorise materials from waste. Sustainability, 9(4), 529.

Schelpenwinning. (n.d.). Retrieved November 28, 2019, from http://www.vliz.be/vleet/content-vleet.php?language=0&id=4337.

Sodium Alginate. (n.d.). Retrieved October 24, 2019, from https://www.modernistpantry.com/sodium-alginate.html.

Sodium Alginate Manufacturing. (n.d.). Retrieved October 24, 2019, from https://www.artmolds.com/sodium-alginate.

Stegall, N. (2006). Designing for sustainability: A philosophy for ecologically intentional design. Design issues, 22(2), 56-63.

Tabriz, A. G., Hermida, M. A., Leslie, N. R., & Shu, W. (2015). Three-dimensional bioprinting of complex cell laden alginate hydrogel structures. Biofabrication, 7(4), 045012.

Tegethoff, F., Rohleder, J., Kroker, E., Calcium Carbonate: From the Cretaceous Period into the 21st century, Brikhäuser Verlag, Basel, 2001.

Terry, B. (2012). Plastic-Free: How I Kicked the Plastic Habit and How You Can Too. Simon and Schuster.

The Circular Economy In Detail. (n.d.). Retrieved October 22, 2019, from https://www.ellenmacarthurfoundation.org/explore/the-circular-economy-in-detail.

Theorganicsolution. (2012, August 15). Alginates, more than just seaweed. Retrieved October 20, 2019, from https://theorganicsolution.wordpress.com/2012/06/01/alginates-more-than-just-seaweed/.

Theorganicsolution. (2012, June 1). Molecular Gastronomy. Retrieved October 12, 2019, from https://theorganicsolution.wordpress.com/tag/molecular-gastronomy/.

The Seaweed Site: information on marine algae. (n.d.). Retrieved October 25, 2019, from http://www.seaweed.ie/descriptions/ascophyllum_nodosum.php.

Trenfield, S. J., Awad, A., Goyanes, A., Gaisford, S., & Basit, A. W. (2018). 3D printing pharmaceuticals: drug development to frontline care. Trends in pharmacological sciences, 39(5), 440-451.

Trouw. (2002). Zeelands Roem. Retrieved from trouw.nl: https:// www.trouw.nl/home/zeelands-roem~a7f60659/

Types of 3D Printing Technology. (2019, October 28). Retrieved October 28, 2019, from https://all3dp.com/1/types-of-3d-printers-3d-printing-technology/.

Tønnesen, H. H., Másson, M., & Loftsson, T. (2002). Studies of curcumin and curcuminoids. XXVII. Cyclodextrin complexation: solubility, chemical and photochemical stability. International Journal of Pharmaceutics, 244(1-2), 127-135.

VanZile, J. (2020, February 10). Learn How to Grow and Care for Areca Palms. Retrieved February 19, 2020, from https://www.thespruce.com/grow-areca-palms-indoors-1902876

Van Wijk, A. J. M., & van Wijk, I. (2015). 3D printing with biomaterials: Towards a sustainable and circular economy. IOS press.

Variavoer. Mensen houden van deze bloemen en planten. Retrieved February 19, 2020, from http://variavoer.blogspot.com/2012/11/mensen-houden-van-deze-bloemen-en.html

Variavoer. Retrieved February 19, 2020, from http://variavoer.blogspot.com/2020/

Verdonk, A. (n.d.). Toevalstreffer wordt topmateriaal. Retrieved December 9, 2019, from https://www.delta.tudelft.nl/article/toevalstreffer-wordt-topmateriaal.

Verroen, S. (2018). Visserij op de Waddenzee in vogelvlucht. Menaldum: De Waddenacademie. Retrieved from Waddenacademie.nl.

Vette, J. (2016). Shining light on mussel shells: The development of a 3D printed and recyclable material. Retrieved September 20, 2019, from https://repository.tudelft.nl/islandora/object/uuid:4f7f5630-b9c2-4bd7-a5b3-f77cd3ba1e9d.

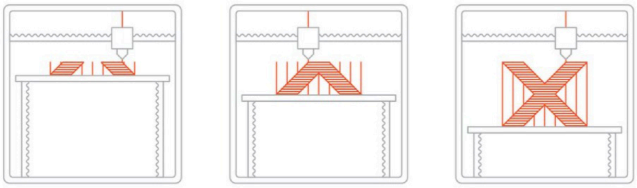
Vezzoli, C. (2014). The "material" side of design for sustainability. In Materials Experience (pp. 105-121). Butterworth-Heinemann.

War on waste: Recycling shells from your plate to benefit the ocean (2017) (accessed 14.10.19), https://www.abc.net.au/news/2017-05-18/war-on-waste-recycling-shells-from-your-plate/8533652

Yang, G., Zhang, L., Peng, T., & Zhong, W. (2000). Effects of Ca2+ bridge cross-linking on structure and pervaporation of cellulose/alginate blend membranes. Journal of Membrane Science, 175(1), 53-60.

Zhong, S., & Pearce, J. M. (2018). Tightening the loop on the circular economy: Coupled distributed recycling and manufacturing with recyclebot and RepRap 3-D printing. Resources, Conservation and Recycling, 128, 48-58.

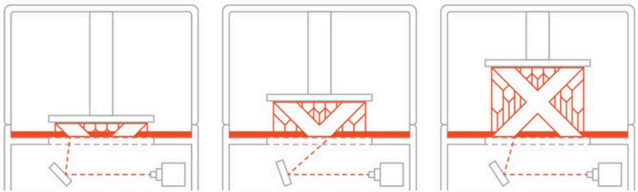
Appendix 2: Types of 3D printing processes



Material extrusion

Material extrusion is a process in which a filament is pushed through a heated nozzle. The material is placed on a base plate with ultimate precision according to a prearranged path. This is the technology this thesis is based on. However, normally this technology uses solid thermoplastic as filament, which solidifies at the base plate to form an solid body. In this thesis a paste is used, which has to dry (instead of solidifying).

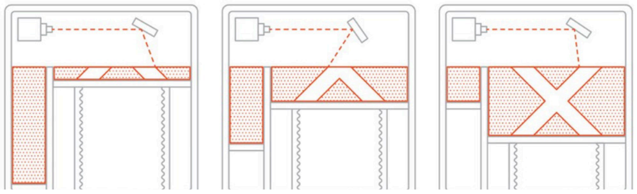
Technologies: FDM/FFF
Materials: Thermoplastics, like ABS, PLA, PET, TPU



VAT polymerization

VAT polymerization is a process in which a light beam precisely cures a photopolymer in a vat. It differs per technology what kind of light source is use (laser for example).

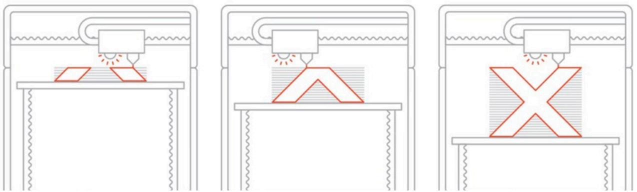
Technologies: SLA, MSLA, DLP
Materials: Photopolymer resin



Powder bed fusion

Powder bed fusion is a process where a thermal source (like a laser or electo beam) is used to fuse powder particles together to create a solid body. In most technologies, the powder gets applied in between the fusion sessions. The unused powder serves as support. In different technologies, this process is used bot for polymers and metals.

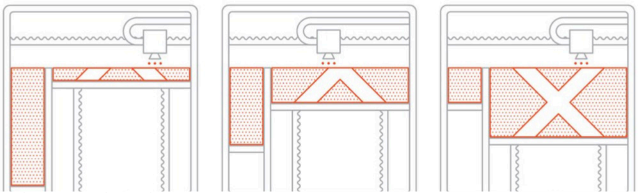
Technologies (polymers): SLS
Technologies (metals): DMLS, SLM, EBM
Materials: Thermoplastic powder (Nylon) or metal powder (aluminium, stainless steel, titanium)



Material jetting

Material jetting is a process in which material droplets gets precisely placed on a building platform. The photopolymer or wax droplets are cured by light. This process allows multi- material and multi-color objects.

Technologies: MJ, DOD
Materials: Photopolymer resin



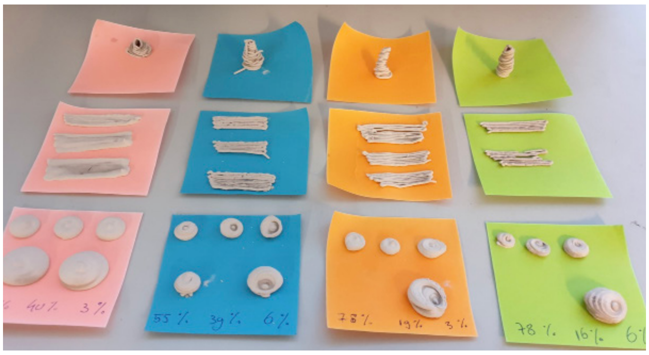
Binder jetting

With binder jetting material powder is binded by selectively adjust a binding agento to the powder bed. It looks like SLS (powder bed fusion), but instead of melting particles togethes, it uses a print head to add droplets of a binding material.

Technologies: BJ
Materials: Sand or metal powder

Source: *https://all3dp.com/1/types-of-3d-printers-3d-printing-technology/*

Appendix 3:
Material composition



In chapter 4 the decision was made to decrease the amount of water used to prepare the paste, based on literature about 3D printing houses and the experience of artist van Herpt. The paste we use, however does not consist of 2 parts (like clay+water or concrete+water), but 3; alginate, mussel shell and water. For that reason a small test was carried out with different compositions, to find out more about the influence each ingedient has. This was of testing can be seen as 'tinkering with the material', as described in the MDD method.
Since in this stage the old printer setup was not strong enough to print more viscous pastes, this was done by hand.

Paste 1 (pink) has the original composition (57%m/40%w/3%a). The processability was very good (easy to mix) and because of the low viscosity the printability was good as well (low resistance). The print quality, however, was quite low since all the details flowed away, and the stability test (upper left corner) did not manage to make a high print.

Paste 2 (blue) has an double amount of alginate (55%m/39%w/6%a). The processability (easy to mix) and printability (low resistance) were good, but since the paste became a bit more viscous it was lower than paste 1. The print quality improved over paste 1 (see picture) since details were kept, and also a higher print was established (so higher stability).

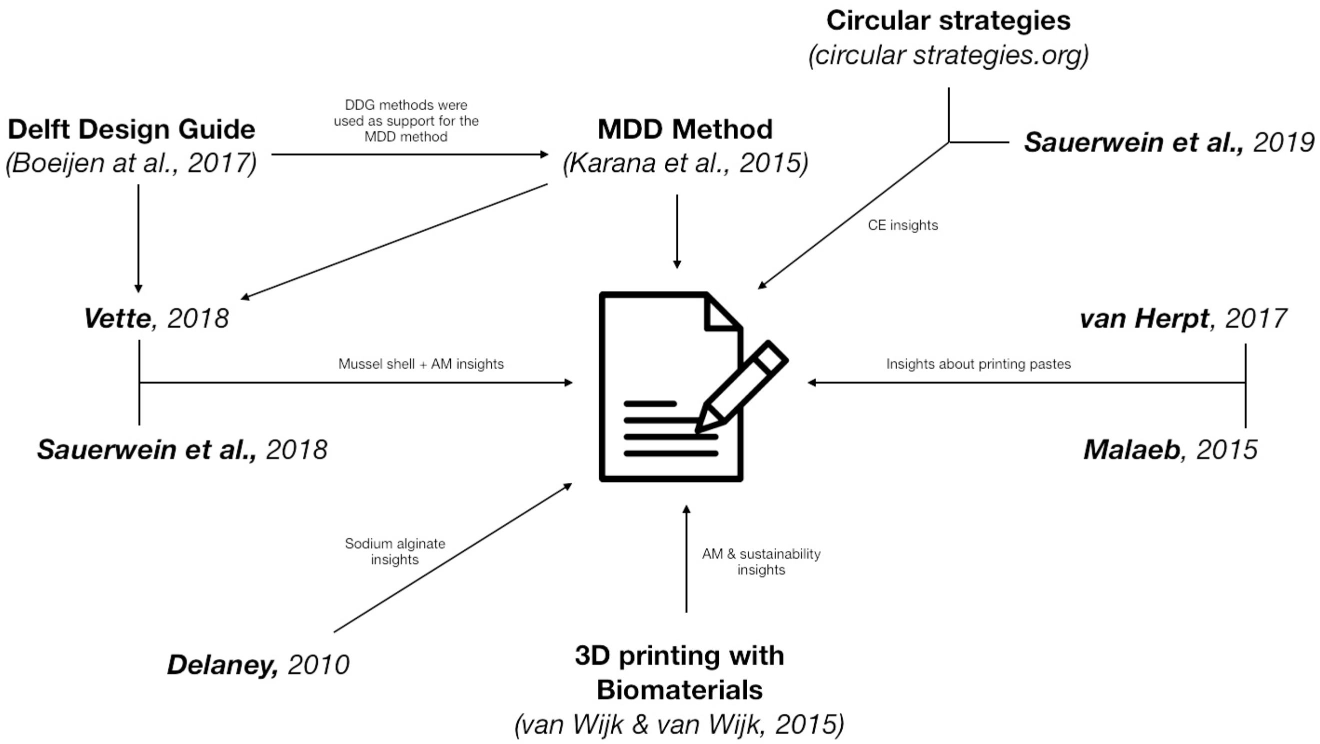
	Processability (easy to mix?)	Printability (does it extrude?)	Quality (details)	Stability (height)
Paste 1	++	++	--	--
Paste 2	+	+	+	+
Paste 3	-	-	++	++
Paste 4	--	--	++	++

Paste 3 (orange) has a double amount of mussel shells (78%m/19%w/3%a). The processability and printability were lower since it was difficult to make a paste with only 19% water. Therefore making a print did require a lot of force. The print quality and print stability did improved a bit over paste 2.

Paste 4 (green) was made with a double amount of both alginate and mussel shells (78%m/16%w/6%a). The processability and printability were really low since it was almost impossible to create the paste and extrude it. The print quality and print stability did not improve significantly compared to paste 3.

Conclusion
The very viscous pastes (paste 3 and 4) did acquire the best print quality and print stability. This proved that the amount of water has to decrease and the amount of mussel shell has to increase to make more detailled and taller prints (just like van herpt and Malaeb stated).
The difference between paste 3 and paste 4 is the amount of alginate. By adding alginate (from 3% to 6%), the quality and stability did not really improve, but the processability and printability became worse. Therefore paste 3 was considered to be the best of the 4.
For the project this means that the amount of 3% alginate will stay untouched. Furthermore, when the new printer set-up is finished, it will be tested how low the amount of water (and high the amount of mussel shell) can go, and when other implications (like layer adhesion loss) will occur.

Appendix 4:
Brief summary of literature phase

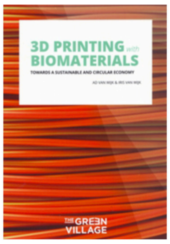


The figure above shows the 10 most used sources for this project.

Used methods are the MDD method (Karana et al.,2015) and the Delft Design Guide (Boeijen et al., 2017). The book 3D printing with Biomaterials is used often for getting insight of the match between AM and CE.
The literature used for understanding the reversible cross linking of sodium alginate is Delaney (2010).
Malaeb (2015), literature about 3D printing houses with concrete and cement, and van Herpt (2017), an artist 3D printing with clay, delivered the insights about decreasing the amount of water and changing the printer setup, based on the setup used by Vette (2018). Sauerwein et al (2018, 2019) provided insights about the link between this AM material and a CE. The circular strategies provided insights on how to match this new product to the circular economy.

Used books:

Delft Design Guide
(Boeijen et at., 2017)



3D printing Biomaterials
(van Wijk & van Wijk., 2015)

Appendix 5:
Experiential characterisation maps

1 N-S

EXPERIENTIAL CHARACTERIZATION MAP

This map aims to support you in understanding how people experience materials.

start →

1 PERFORMATIVE LEVEL

What does the material make you do? 2 →

How do you touch the material?

- [✓ pressing]
- [✓ rubbing]
- grazing
- compressing
- poking
- caressing
- fiddling
- pounding
- pushing
- ....

How do you move the material?

- folding
- [✓ lifting]
- [✓ weighing]
- bending
- flexing
- picking
- squeezing
- smelling

How do you hold the material

- [✓ holding]
- seizing
- pinching
- grabbing
- grasping
- ....

2. SENSORIAL LEVEL

3 →

How would you describe the material?

	2	1	0	1	2	
hard	●	○	○	○	○	soft
smooth	○	○	○	●	○	rough
matte	○	●	○	○	○	glossy
not reflective	●	○	○	○	○	reflective
cold	○	○	●	○	○	warm
not elastic	●	○	○	○	○	elastic
opaque	●	○	○	○	○	transparent
tough	○	○	○	●	○	ductile
strong	○	○	○	●	○	weak
light	○	●	○	○	○	heavy
regular texture	○	○	○	●	○	irregular texture
fibred	○	○	○	●	○	not-fibred

4. INTERPRETIVE LEVEL

What do you associate with the material?

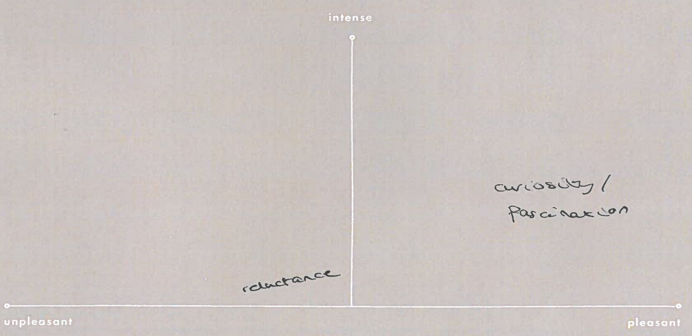
How would you describe it?

meaning 1	meaning 2	meaning 3
natural	futuristic	strange

↓ 5 (unfold the map and open sidewings)

3. AFFECTIVE LEVEL

What emotions does the material elict?



← 4

5. FINAL REFLECTIONS

Why do you think the material is...?

What is the most pleasant quality of the material?	What is the most disturbing quality of the material?	What is the most unique quality of the material?
uneven	feels weird (rough?)	smooth uneven (?)

N-S 2

EXPERIENTIAL CHARACTERIZATION MAP

This map aims to support you in understanding how people experience materials.

start →

1 PERFORMATIVE LEVEL

What does the material make you do? 2 →

How do you touch the material?

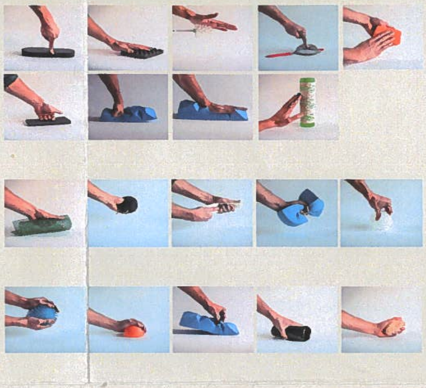
- pressing
- [✓ rubbing]
- grazing
- compressing
- poking
- caressing
- fiddling
- pounding
- pushing
- ....

How do you move the material?

- folding
- lifting
- [✓ weighing]
- bending
- flexing
- picking
- squeezing
- smelling
- [✓ Turning]

How do you hold the material

- holding
- seizing
- pinching
- grabbing
- grasping
- ....



2. SENSORIAL LEVEL

3 →

How would you describe the material?

	2	1	0	1	2	
hard	○	●	○	○	○	soft
smooth	○	○	○	●	○	rough
matte	●	○	○	○	○	glossy
not reflective	●	○	○	○	○	reflective
cold	○	○	●	○	○	warm
not elastic	●	○	○	○	○	elastic
opaque	●	○	○	○	○	transparent
tough	●	○	○	○	○	ductile
strong	○	●	○	○	○	weak
light	●	○	○	○	○	heavy
regular texture	○	○	○	○	●	irregular texture
fibred	○	●	○	○	○	not-fibred

4. INTERPRETIVE LEVEL

What do you associate with the material?

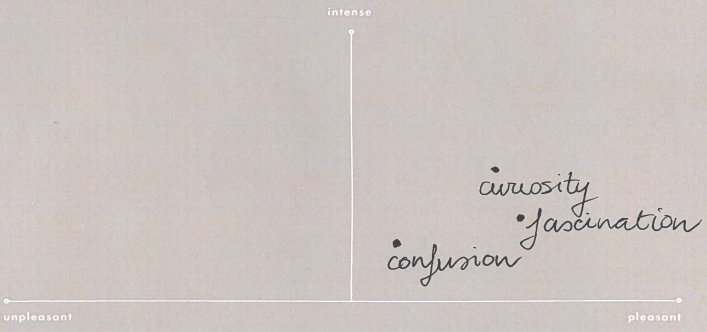
How would you describe it?

meaning 1	meaning 2	meaning 3
natural	sober	hand-crafted.
color.	simpel material.	non symetric

↓ 5 (unfold the map and open sidewings)

3. AFFECTIVE LEVEL

What emotions does the material elict?



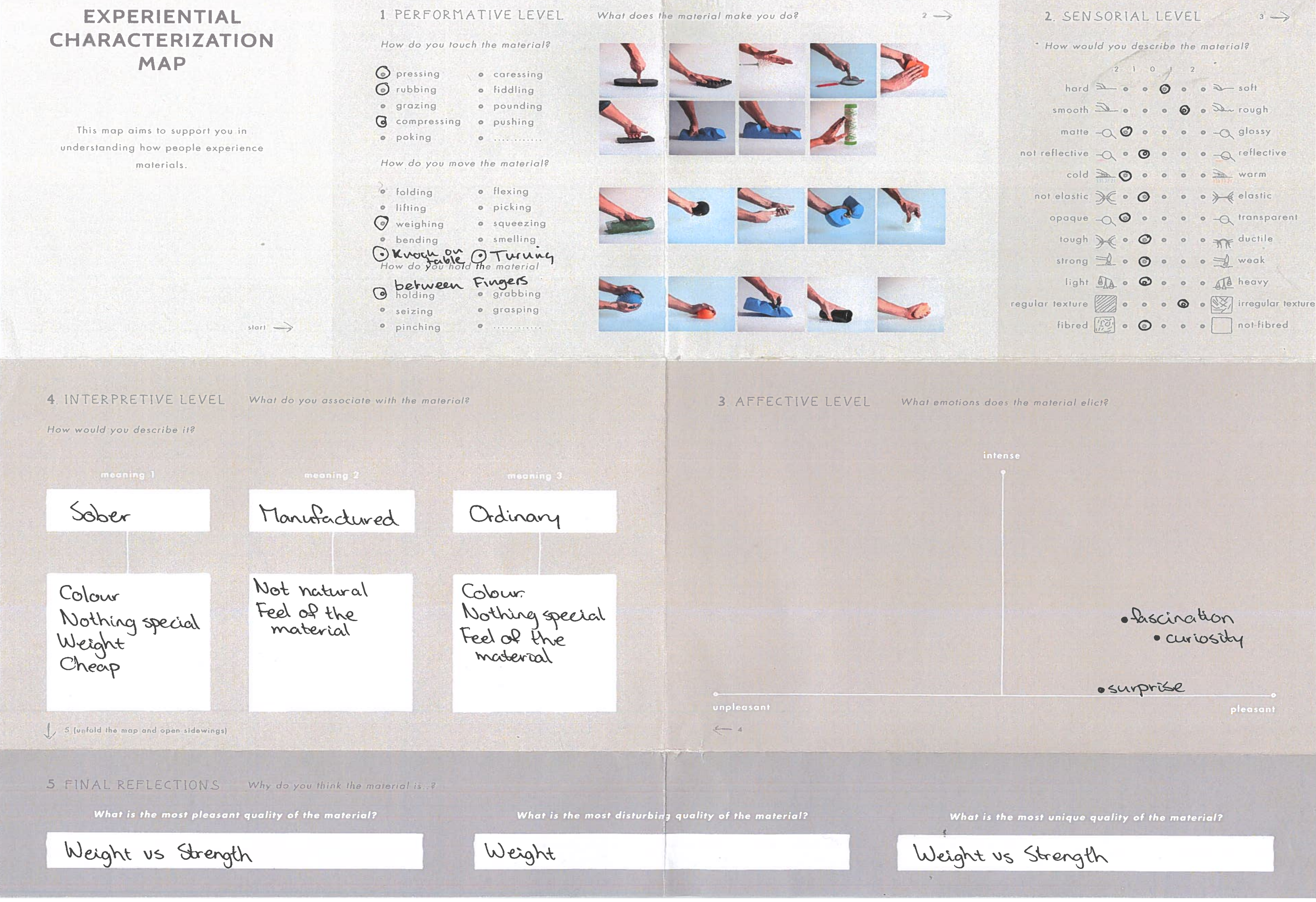
← 4

5. FINAL REFLECTIONS

Why do you think the material is...?

What is the most pleasant quality of the material?	What is the most disturbing quality of the material?	What is the most unique quality of the material?
light	to rough	natural look.

N-S 3



EXPERIENTIAL CHARACTERIZATION MAP

This map aims to support you in understanding how people experience materials.

start →

1. PERFORMATIVE LEVEL

What does the material make you do? 2 →

How do you touch the material?

● pressing
● rubbing
○ grazing
● compressing
○ poking
○ caressing
○ fiddling
○ pounding
○ pushing
○ …………

How do you move the material?

○ folding
○ lifting
● weighing
○ bending
● Knock on table
○ flexing
○ picking
○ squeezing
○ smelling
● Turning

How do you hold the material

between Fingers

● holding
○ seizing
○ pinching
○ grabbing
○ grasping
○ …………

2. SENSORIAL LEVEL

3 →

How would you describe the material?

	2	1	0	1	2	
hard	○	○	●	○	○	soft
smooth	○	○	○	●	○	rough
matte	●	○	○	○	○	glossy
not reflective	○	●	○	○	○	reflective
cold	●	○	○	○	○	warm
not elastic	○	●	○	○	○	elastic
opaque	●	○	○	○	○	transparent
tough	○	●	○	○	○	ductile
strong	○	●	○	○	○	weak
light	○	●	○	○	○	heavy
regular texture	○	○	○	●	○	irregular texture
fibred	○	●	○	○	○	not-fibred

4. INTERPRETIVE LEVEL

What do you associate with the material?

How would you describe it?

meaning 1	meaning 2	meaning 3
Sober	Manufactured	Ordinary
Colour Nothing special Weight Cheap	Not natural Feel of the material	Colour Nothing special Feel of the material

↓ 5 (unfold the map and open sidewings)

3. AFFECTIVE LEVEL

What emotions does the material elict?

intense

unpleasant

pleasant

• fascination
• curiosity
• surprise

← 4

5. FINAL REFLECTIONS

Why do you think the material is..?

What is the most pleasant quality of the material?	*What is the most disturbing quality of the material?*	*What is the most unique quality of the material?*
Weight vs Strength	Weight	Weight vs Strength

N-S 4

EXPERIENTIAL CHARACTERIZATION MAP

This map aims to support you in understanding how people experience materials.

start →

1. PERFORMATIVE LEVEL

What does the material make you do? 2 →

How do you touch the material?

● pressing
● rubbing
○ grazing
● compressing
○ poking
○ caressing
○ fiddling
○ pounding
○ pushing
○ …………

How do you move the material?

○ folding
● lifting
● weighing
○ bending
● Knock on table
○ flexing
○ picking
○ squeezing
○ smelling
● Turning

How do you hold the material

● holding
○ seizing
○ pinching
○ grabbing
○ grasping
○ …………

2. SENSORIAL LEVEL

3 →

How would you describe the material?

	2	1	0	1	2	
hard	○	●	○	○	○	soft
smooth	○	○	●	○	○	rough
matte	○	○	○	●	○	glossy
not reflective	○	●	○	○	○	reflective
cold	○	○	●	○	○	warm
not elastic	○	○	●	○	○	elastic
opaque	●	○	○	○	○	transparent
tough	○	○	○	●	○	ductile
strong	○	○	○	●	○	weak
light	○	●	○	○	○	heavy
regular texture	○	○	●	○	○	irregular texture
fibred	○	○	○	●	○	not-fibred

4. INTERPRETIVE LEVEL

What do you associate with the material?

How would you describe it?

meaning 1	meaning 2	meaning 3
toy-like	hand-crafted	sober
geschikt voor speelgoed	uitnodigend om mee aan de gang te gaan	kleurloos

↓ 5 (unfold the map and open sidewings)

3. AFFECTIVE LEVEL

What emotions does the material elict?

intense

unpleasant

pleasant

• ~~me~~lancholy
• Reluctance
• comfort
• melancholy

← 4

5. FINAL REFLECTIONS

Why do you think the material is..?

What is the most pleasant quality of the material?	*What is the most disturbing quality of the material?*	*What is the most unique quality of the material?*
elastisch	saai kleur	sterk

W-S 5

EXPERIENTIAL CHARACTERIZATION MAP

This map aims to support you in understanding how people experience materials.

start →

1. PERFORMATIVE LEVEL

What does the material make you do? 2 →

How do you touch the material?

- ○ pressing
- [✓ rubbing]
- ○ grazing
- [✓ compressing] test strength
- ○ poking
- ○ caressing
- ○ fiddling
- ○ pounding
- ○ pushing
- ○ …………

How do you move the material?

- ○ folding
- ○ lifting
- [✓ weighing]
- ○ bending
- [✓ knock on table]
- ○ flexing
- ○ picking
- ○ squeezing
- ○ smelling
- [✓ Turn]

How do you hold the material

- [✓ holding] between 2 Fingers
- ○ seizing
- ○ pinching
- ○ grabbing
- ○ grasping
- ○ …………

2. SENSORIAL LEVEL

3 →

How would you describe the material?

	2	1	0	1	2	
hard	●	○	○	○	○	soft
smooth	●	○	○	○	○	rough
matte	○	●	○	✗	○	glossy
not reflective	●	○	○	○	✗	reflective
cold	○	○	○	●	○	warm
not elastic	●	○	○	○	✗	elastic
opaque	●	○	○	○	✗	transparent
tough	○	●	○	○	○	ductile
strong	○	○	●	○	○	weak
light	●	○	○	○	○	heavy
regular texture	○	●	○	○	○	irregular texture
fibred	○	○	○	●	○	not-fibred

4. INTERPRETIVE LEVEL

What do you associate with the material?

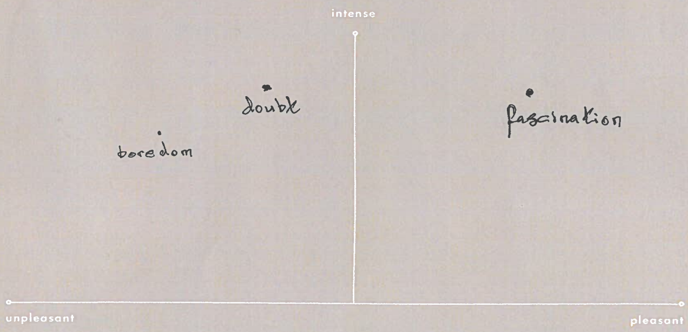
How would you describe it?

meaning 1	meaning 2	meaning 3
sober	natural	hand-crafted
kleur textuur glans	pasta kleur	onregelmatig broos kwetsbaar } qua uitstraling

↓ 5 (unfold the map and open sidewings)

3. AFFECTIVE LEVEL

What emotions does the material elicit?



← 4

5. FINAL REFLECTIONS

Why do you think the material is…?

What is the most pleasant quality of the material? gevoel

What is the most disturbing quality of the material? kleur

What is the most unique quality of the material? gewicht

---

(6)

EXPERIENTIAL CHARACTERIZATION MAP

This map aims to support you in understanding how people experience materials.

start →

1. PERFORMATIVE LEVEL

What does the material make you do? 2 →

How do you touch the material?

- [✓ pressing]
- [✓ rubbing]
- ○ grazing
- ○ compressing
- ○ poking
- [✓ caressing]
- ○ fiddling
- ○ pounding
- ○ pushing
- ○ …………

How do you move the material?

- ○ folding
- ○ lifting
- ○ weighing
- ○ bending
- [✓ Thicking]
- ○ flexing
- ○ picking
- ○ squeezing
- ○ smelling
- [✓ Turning]

How do you hold the material

- [✓ holding]
- ○ seizing
- ○ pinching
- ○ grabbing
- ○ grasping
- ○ …………

2. SENSORIAL LEVEL

3 →

How would you describe the material?

	2	1	0	1	2	
hard	○	●	○	○	○	soft
smooth	○	●	○	○	○	rough
matte	●	○	○	○	○	glossy
not reflective	●	○	○	○	○	reflective
cold	○	○	●	○	○	warm
not elastic	●	○	○	○	○	elastic
opaque	●	○	○	○	○	transparent
tough	●	○	○	○	○	ductile
strong	○	○	●	○	○	weak
light	●	○	○	○	○	heavy
regular texture	●	○	○	○	○	irregular texture
fibred	○	●	○	○	○	not-fibred

4. INTERPRETIVE LEVEL

What do you associate with the material?

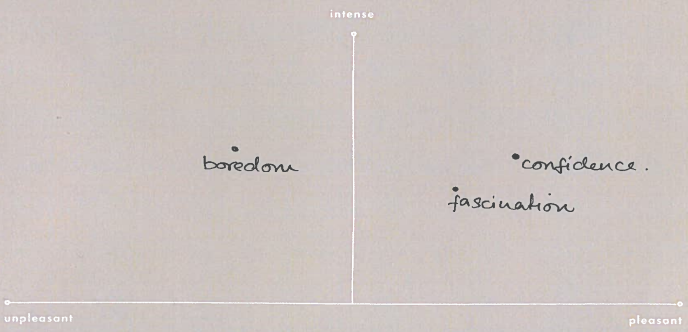
How would you describe it?

meaning 1	meaning 2	meaning 3
Natural.	Nostalgic	
- organic form and finish. - The texture	- sense of aging	

↓ 5 (unfold the map and open sidewings)

3. AFFECTIVE LEVEL

What emotions does the material elicit?



← 4

5. FINAL REFLECTIONS

Why do you think the material is…?

What is the most pleasant quality of the material? Light weight.

What is the most disturbing quality of the material? Grainy texture.

What is the most unique quality of the material? weight to strength perception.

⑦

EXPERIENTIAL CHARACTERIZATION MAP

This map aims to support you in understanding how people experience materials.

start →

1. PERFORMATIVE LEVEL

What does the material make you do? 2 →

How do you touch the material?

- ● pressing
- ● rubbing
- ○ grazing
- ○ compressing
- ○ poking
- ● caressing
- ○ fiddling
- ○ pounding
- ○ pushing
- ○ …………

How do you move the material?

- ○ folding
- ○ lifting
- ○ weighing
- ○ bending
- ○
- ○ flexing
- ○ picking
- ○ squeezing
- ○ smelling
- ● Turning

How do you hold the material

- ● holding
- ○ seizing
- ○ pinching
- ○ grabbing
- ○ grasping
- ○ …………

2. SENSORIAL LEVEL

3 →

How would you describe the material?

	-2	-1	0	1	2	
hard	○	○	●	○	○	soft
smooth	○	●	○	○	○	rough
matte	●	○	○	○	○	glossy
not reflective	○	●	○	○	○	reflective
cold	○	●	○	○	○	warm
not elastic	●	○	○	○	○	elastic
opaque	●	○	○	○	○	transparent
tough	○	●	○	○	○	ductile
strong	○	○	○	○	●	weak
light	●	○	○	○	○	heavy
regular texture ▨	○	○	○	●	○	irregular texture
fibred	○	○	○	●	○	not-fibred

4. INTERPRETIVE LEVEL

What do you associate with the material?

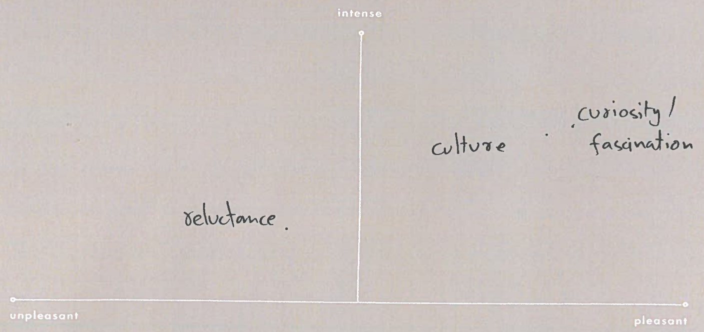
How would you describe it?

meaning 1	meaning 2	meaning 3
Toy-like	Hand-crafted	Ordinary
• Easy to make into a toy • Easy to play • Safe.	• Uneven texture. • Drips/overflows. • Imperfections make it look hand made.	• Could be part of everyday life. • Not out of box.

↓ 5 (unfold the map and open sidewings)

3. AFFECTIVE LEVEL

What emotions does the material elict?



← 4

5. FINAL REFLECTIONS

Why do you think the material is..?

What is the most pleasant quality of the material?	What is the most disturbing quality of the material?	What is the most unique quality of the material?
Slight cold to touch, imperfections	Looks fragile, Brittle.	You can decide shape & roughness (finish)

---

⑧

EXPERIENTIAL CHARACTERIZATION MAP

This map aims to support you in understanding how people experience materials.

start →

1. PERFORMATIVE LEVEL

What does the material make you do? 2 →

How do you touch the material?

- ● pressing
- ● rubbing
- ○ grazing
- ● compressing
- ○ poking
- ○ caressing
- ○ fiddling
- ○ pounding
- ● pushing
- ○ …………

How do you move the material?

- ○ folding
- ○ lifting
- ● weighing
- ● bending
- ○ flexing
- ○ picking
- ○ squeezing
- ○ smelling
- ● Turning

How do you hold the material

- ● holding
- ○ seizing
- ● pinching
- ○ grabbing
- ○ grasping
- ○ …………

2. SENSORIAL LEVEL

3 →

How would you describe the material?

	-2	-1	0	1	2	
hard	○	●	○	○	○	soft
smooth	○	○	○	●	○	rough
matte	●	○	○	○	○	glossy
not reflective	●	○	○	○	○	reflective
cold	○	○	○	●	○	warm
not elastic	●	○	○	○	○	elastic
opaque	●	○	○	○	○	transparent
tough	●	○	○	○	○	ductile
strong	○	○	○	○	●	weak
light	○	●	○	○	○	heavy
regular texture ▨	○	○	○	●	○	irregular texture
fibred	○	○	●	○	○	not-fibred

4. INTERPRETIVE LEVEL

What do you associate with the material?

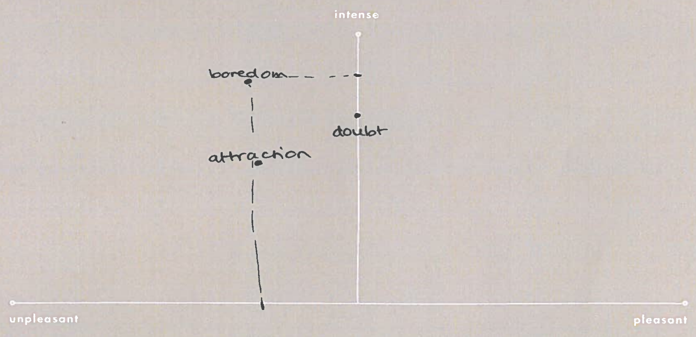
How would you describe it?

meaning 1	meaning 2	meaning 3
sober	calm	natural
- kleur - mat gevoel - scheuren	- niet schreeuwerig - serieus	- door kleur en structuur

↓ 5 (unfold the map and open sidewings)

3. AFFECTIVE LEVEL

What emotions does the material elict?



← 4

5. FINAL REFLECTIONS

Why do you think the material is..?

What is the most pleasant quality of the material?	What is the most disturbing quality of the material?	What is the most unique quality of the material?
Calm	Ziet er broos uit	Voelt warm aan

(9)

EXPERIENTIAL CHARACTERIZATION MAP

This map aims to support you in understanding how people experience materials.

start →

1 PERFORMATIVE LEVEL

What does the material make you do? 2 →

How do you touch the material?

- [✓ pressing]
- [✓ rubbing]
- grazing
- compressing
- poking
- [✓ caressing]
- fiddling
- pounding
- pushing
- ....

How do you move the material?

- folding
- lifting
- weighing
- bending
- [✓ Turning]
- flexing
- picking
- squeezing
- smelling
- [✓ Thiching]

How do you hold the material

- [✓ holding]
- seizing
- pinching
- grabbing
- grasping
- ....

2. SENSORIAL LEVEL

3 →

How would you describe the material?

		-2	-1	0	1	2	
hard		○	●	○	○	○	soft
smooth		○	○	○	●	○	rough
matte		●	○	○	○	○	glossy
not reflective		●	○	○	○	○	reflective
cold		○	○	●	○	○	warm
not elastic		●	○	○	○	○	elastic
opaque		●	○	○	○	○	transparent
tough		●	○	○	○	○	ductile
strong		○	○	●	○	○	weak
light		●	○	○	○	○	heavy
regular texture	▨	○	●	○	○	○	irregular texture
fibred		○	○	○	●	○	not-fibred

4. INTERPRETIVE LEVEL

What do you associate with the material?

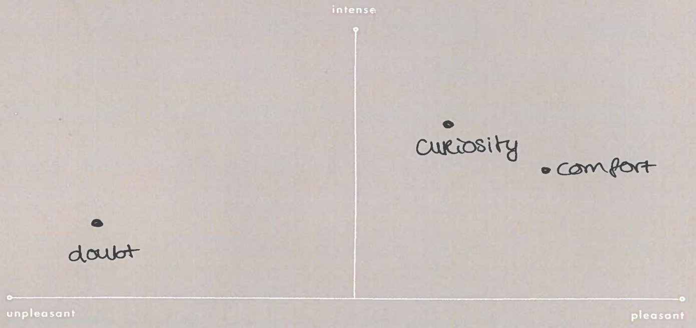
How would you describe it?

meaning 1	meaning 2	meaning 3
~~hand~~ manufactured	hand-crafted	calm
• visibly made with machine, but →	• many options for personalisation	• Door beetje ruw oppervlak komt het zachtaardig over

↓ 5 (unfold the map and open sidewings)

3. AFFECTIVE LEVEL

What emotions does the material elict?



← 4

5. FINAL REFLECTIONS

Why do you think the material is..?

What is the most pleasant quality of the material?	What is the most disturbing quality of the material?	What is the most unique quality of the material?
zachtaardig ~~voel~~ aanvoelend	bros, durf geen kracht ~~te~~ zetten	veel opties in verwerking

---

(10)

EXPERIENTIAL CHARACTERIZATION MAP

This map aims to support you in understanding how people experience materials.

start →

1 PERFORMATIVE LEVEL

What does the material make you do? 2 →

How do you touch the material?

- pressing
- [✓ rubbing]
- grazing
- [✓ compressing]
- poking
- [✓ caressing]
- fiddling
- pounding
- pushing
- ....

How do you move the material?

- folding
- lifting
- weighing
- bending
- [✓ Turning]
- flexing
- picking
- squeezing
- smelling
- [✓ Thiching]

How do you hold the material

- [✓ holding]
- seizing
- pinching
- grabbing
- grasping
- ....

2. SENSORIAL LEVEL

3 →

How would you describe the material?

		-2	-1	0	1	2	
hard		○	○	[✓ ○]	○	○	soft
smooth		○	[✓ ○]	○	○	○	rough
matte		[✓ ○]	○	○	○	○	glossy
not reflective		[✓ ○]	○	○	○	○	reflective
cold		○	○	○	[✓ ○]	○	warm
not elastic		[✓ ○]	○	○	○	○	elastic
opaque		[✓ ○]	○	○	○	○	transparent
tough		○	[✓ ○]	○	○	○	ductile
strong		○	○	[✓ ○]	○	○	weak
light		○	[✓ ○]	○	○	○	heavy
regular texture	▨	○	○	○	[✓ ○]	○	irregular texture
fibred		○	[✓ ○]	○	○	○	not-fibred

4. INTERPRETIVE LEVEL

What do you associate with the material?

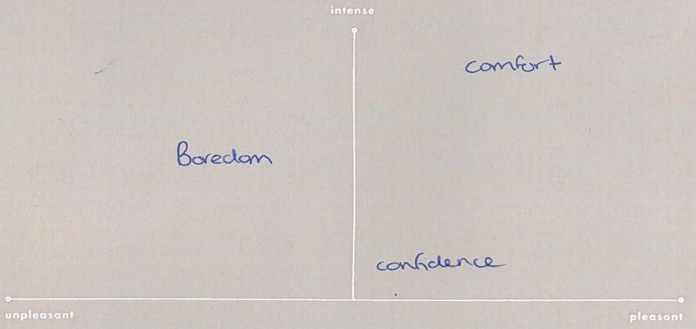
How would you describe it?

meaning 1	meaning 2	meaning 3
Not sexy	Hand-crafted	Natural
→ Duf → Beetje viezig → Niet bijzonder	→ De vorm (ovaal telt dat miss niet) → Gerecycled	→ Heeft iets weg van de kruising tussen papier en hout → Niet echt plastic achtig

↓ 5 (unfold the map and open sidewings)

3. AFFECTIVE LEVEL

What emotions does the material elict?



← 4

5. FINAL REFLECTIONS

Why do you think the material is..?

What is the most pleasant quality of the material?	What is the most disturbing quality of the material?	What is the most unique quality of the material?
Het is licht	Viezig (neemt viezigheid op)	De niet plastic look (verwachting is wel dat het plastic is)

11

EXPERIENTIAL CHARACTERIZATION MAP

This map aims to support you in understanding how people experience materials.

start →

1. PERFORMATIVE LEVEL

What does the material make you do? 2 →

How do you touch the material?

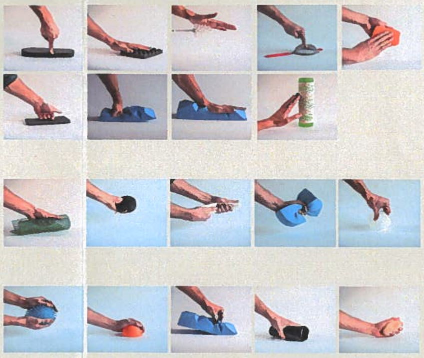
● pressing	○ caressing
● rubbing	○ fiddling
○ grazing	○ pounding
○ compressing	○ pushing
○ poking	○ …………

How do you move the material?

○ folding	○ flexing
○ lifting	○ picking
○ weighing	○ squeezing
● bending	● smelling
	● Turning

How do you hold the material

● holding	○ grabbing
○ seizing	○ grasping
○ pinching	○ …………



2. SENSORIAL LEVEL

3 →

How would you describe the material?

	-2	-1	0	1	2	
hard	○	●	○	○	○	soft
smooth	○	●	○	○	○	rough
matte	○	●	○	○	○	glossy
not reflective	○	○	○	●	○	reflective
cold	○	●	○	○	○	warm
not elastic	○	●	○	○	○	elastic
opaque	○	○	●	○	○	transparent
tough	○	○	○	○	●	ductile
strong	○	○	○	○	●	weak
light	●	○	○	○	○	heavy
regular texture	○	○	○	●	○	irregular texture
fibred	○	●	○	○	○	not-fibred

4. INTERPRETIVE LEVEL

What do you associate with the material?

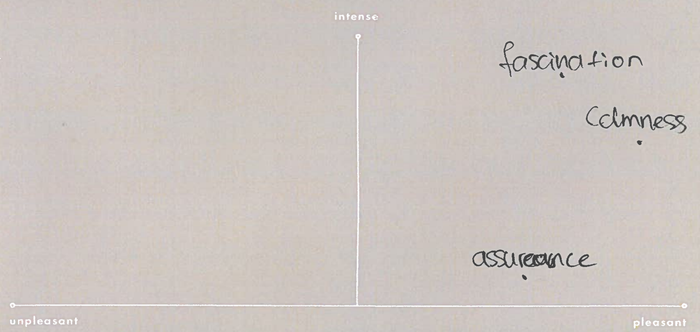
How would you describe it?

meaning 1	meaning 2	meaning 3
hand-crafted	calm	natural
• patterns • weight	• weight	• look and feel

↓ 5 (unfold the map and open sidewings)

3. AFFECTIVE LEVEL

What emotions does the material elicit?



← 4

5. FINAL REFLECTIONS

Why do you think the material is..?

What is the most pleasant quality of the material?	What is the most disturbing quality of the material?	What is the most unique quality of the material?
• feels really pleasant in the hands	• fragile (might break)	• Calmness (has asense of tranquility)

12

EXPERIENTIAL CHARACTERIZATION MAP

This map aims to support you in understanding how people experience materials.

start →

1. PERFORMATIVE LEVEL

What does the material make you do? 2 →

How do you touch the material?

○ pressing	○ caressing
● rubbing	○ fiddling
○ grazing	○ pounding
○ compressing	○ pushing
○ poking	● Scratch

How do you move the material?

○ folding	○ flexing
○ lifting	○ picking
○ weighing	○ squeezing
○ bending	○ smelling
● thicking	● Turning

How do you hold the material

● holding	○ grabbing
○ seizing	○ grasping
○ pinching	○ …………

2. SENSORIAL LEVEL

3 →

How would you describe the material?

	-2	-1	0	1	2	
hard	○	●	○	○	○	soft
smooth	○	○	○	●	○	rough
matte	●	○	○	○	○	glossy
not reflective	●	○	○	○	○	reflective
cold	○	●	○	○	○	warm
not elastic	●	○	○	○	○	elastic
opaque	○	●	○	○	○	transparent
tough	○	○	○	○	●	ductile
strong	○	○	○	●	○	weak
light	○	○	●	○	○	heavy
regular texture	○	○	○	●	○	irregular texture
fibred	○	●	○	○	○	not-fibred

4. INTERPRETIVE LEVEL

What do you associate with the material?

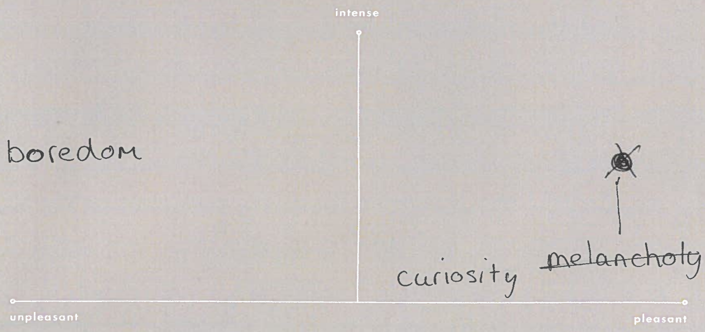
How would you describe it?

meaning 1	meaning 2	meaning 3
Not sexy	Natural	Strange
• bit old-fashioned look & feel. •	• feels like stone • color looks natural	Feels like a combination between modern manufacturing methods and amore old school material.

↓ 5 (unfold the map and open sidewings)

3. AFFECTIVE LEVEL

What emotions does the material elicit?



← 4

5. FINAL REFLECTIONS

Why do you think the material is..?

What is the most pleasant quality of the material?	What is the most disturbing quality of the material?	What is the most unique quality of the material?
Natural look + Feel	Feels a bit weak	Natural look + feel

⑬

EXPERIENTIAL CHARACTERIZATION MAP

This map aims to support you in understanding how people experience materials.

start →

1 PERFORMATIVE LEVEL

What does the material make you do?

2 →

How do you touch the material?

- [✓ pressing]
- [✓ rubbing]
- grazing
- compressing
- poking
- caressing
- fiddling
- pounding
- [✓ pushing]
- …………

How do you move the material?

- folding
- lifting
- weighing
- [✓ bending]
- [✓ Thicking]
- flexing
- picking
- squeezing
- smelling
- [✓ Turning]

How do you hold the material

- [✓ holding]
- seizing
- [✓ pinching]
- grabbing
- grasping
- …………

2. SENSORIAL LEVEL

3 →

How would you describe the material?

	-2	-1	0	1	2	
hard	○	●	○	○	○	soft
smooth	○	○	○	●	○	rough
matte	●	○	○	○	○	glossy
not reflective	●	○	○	○	○	reflective
cold	○	○	○	●	○	warm
not elastic	○	○	●	○	○	elastic
opaque	●	○	○	○	○	transparent
tough	○	○	●	○	○	ductile
strong	○	○	●	○	○	weak
light	○	●	○	○	○	heavy
regular texture	○	○	○	○	●	irregular texture
fibred	○	●	○	○	○	not-fibred

4. INTERPRETIVE LEVEL

What do you associate with the material?

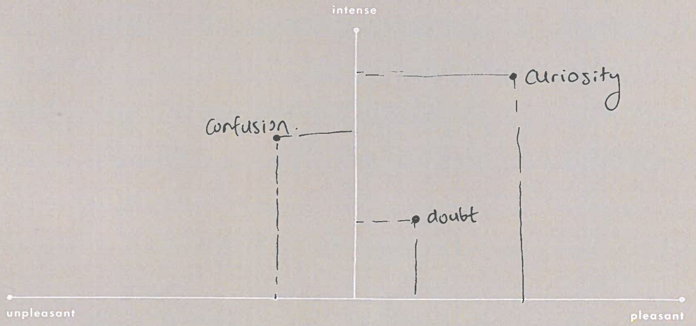
How would you describe it?

meaning 1	meaning 2	meaning 3
hand-crafted	calm	natural
The way of producing even though it's like 3D printing (layer-by-layer) it's looks like its handmade because of its imperfect look.	The color [illegible] of the material and probably because of the chosen shape even though its not the case	It feels like the material result differently in every manufacturing attempt.

↓ 5 (unfold the map and open sidewings)

3. AFFECTIVE LEVEL

What emotions does the material elict?



← 4

5. FINAL REFLECTIONS

Why do you think the material is..?

What is the most pleasant quality of the material?	What is the most disturbing quality of the material?	What is the most unique quality of the material?
The curiosity it creates. The material itself looks elastic but also really durable.	The cracks at the bottom might influence the overall quality.	Imperfect result, can be beneficial for personalized products.

---

⑭

EXPERIENTIAL CHARACTERIZATION MAP

This map aims to support you in understanding how people experience materials.

start →

1 PERFORMATIVE LEVEL

What does the material make you do?

2 →

How do you touch the material?

- [✓ pressing]
- [✓ rubbing]
- grazing
- compressing
- poking
- caressing
- fiddling
- pounding
- pushing
- [✓ knocks]
- [✓ Scratch]

How do you move the material?

- folding
- lifting
- weighing
- bending
- flexing
- picking
- squeezing
- smelling
- [✓ Turning]

How do you hold the material

- [✓ holding]
- seizing
- [✓ pinching]
- grabbing
- grasping
- …………

2. SENSORIAL LEVEL

3 →

How would you describe the material?

	-2	-1	0	1	2	
hard	○	●	○	○	○	soft
smooth	○	○	○	●	○	rough
matte	●	○	○	○	○	glossy
not reflective	●	○	○	○	○	reflective
cold	○	○	●	○	○	warm
not elastic	○	●	○	○	○	elastic
opaque	●	○	○	○	○	transparent
tough	○	●	○	○	○	ductile
strong	○	○	○	●	○	weak
light	○	●	○	○	○	heavy
regular texture	○	○	●	○	○	irregular texture
fibred	○	●	○	○	○	not-fibred

4. INTERPRETIVE LEVEL

What do you associate with the material?

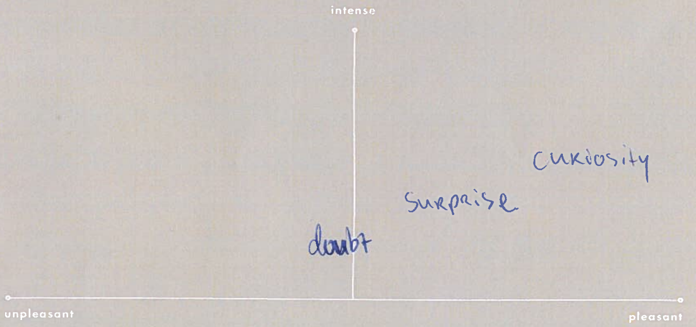
How would you describe it?

meaning 1	meaning 2	meaning 3
Natural	hand-crafted	Strange
• Seams like a natural product on eye-sight	the layered structure + color gives me a feeling of hand-craft.	I cant directly make a connection between how it looks and feels sounds

↓ 5 (unfold the map and open sidewings)

3. AFFECTIVE LEVEL

What emotions does the material elict?



← 4

5. FINAL REFLECTIONS

Why do you think the material is..?

What is the most pleasant quality of the material?	What is the most disturbing quality of the material?	What is the most unique quality of the material?
it is lighter then I would expect.	ticking the sound did not connect with the looks.	

15

EXPERIENTIAL CHARACTERIZATION MAP

This map aims to support you in understanding how people experience materials.

start →

1. PERFORMATIVE LEVEL

What does the material make you do? 2 →

How do you touch the material?

- ○ pressing
- [✓ ○ rubbing]
- ○ grazing
- ○ compressing
- ○ poking
- ○ caressing
- ○ fiddling
- ○ pounding
- ○ pushing
- [✓ ○ Scratch]
- [✓ ○ Knocks]

How do you move the material?

- ○ folding
- ○ lifting
- ○ weighing
- ○ bending
- ○ flexing
- ○ picking
- ○ squeezing
- ○ smelling
- [✓ ○ Turning]

How do you hold the material

- [✓ ○ holding]
- ○ seizing
- ○ pinching
- ○ grabbing
- ○ grasping
- ○ …………

2. SENSORIAL LEVEL

3 →

How would you describe the material?

	2	-1	0	1	2	
hard	[✓ ○]	○	○	○	○	soft
smooth	○	[✓ ○]	○	○	○	rough
matte	○	[✓ ○]	○	○	○	glossy
not reflective	[✓ ○]	○	○	○	○	reflective
cold	○	○	[✓ ○]	○	○	warm
not elastic	[✓ ○]	○	○	○	○	elastic
opaque	[✓ ○]	○	○	○	○	transparent
tough	[✓ ○]	○	○	○	○	ductile
strong	○	○	○	[✓ ○]	○	weak
light	○	○	[✓ ○]	○	○	heavy
regular texture	○	○	[✓ ○]	○	○	irregular texture
fibred	○	○	[✓ ○]	○	○	not-fibred

4. INTERPRETIVE LEVEL

What do you associate with the material?

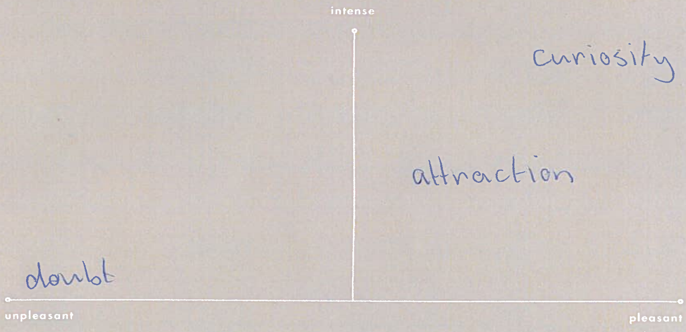
How would you describe it?

meaning 1	meaning 2	meaning 3
natural	hand crafted	futuristic
- 'color' - texture	- Print quality - ceramic	- light/strength - bio based?

↓ 5 (unfold the map and open sidewings)

3. AFFECTIVE LEVEL

What emotions does the material elict?



← 4

5. FINAL REFLECTIONS

Why do you think the material is..?

What is the most pleasant quality of the material?

Look & feel

What is the most disturbing quality of the material?

manufacture quality

What is the most unique quality of the material?

Strength + stiffness/weight is good enoug to compete with plastics

---

16

EXPERIENTIAL CHARACTERIZATION MAP

This map aims to support you in understanding how people experience materials.

start →

1. PERFORMATIVE LEVEL

What does the material make you do? 2 →

How do you touch the material?

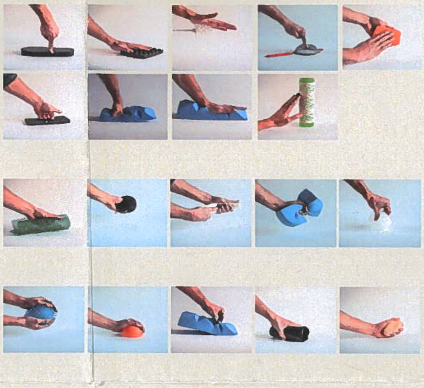
- [✓ ○ pressing]
- [✓ ○ rubbing]
- ○ grazing
- [✓ ○ compressing]
- ○ poking
- [✓ ○ caressing]
- ○ fiddling
- ○ pounding
- ○ pushing
- ○ …………

How do you move the material?

- ○ folding
- ○ lifting
- ○ weighing
- [✓ ○ bending]
- ○ flexing
- ○ picking
- ○ squeezing
- ○ smelling

How do you hold the material

- [✓ ○ holding]
- ○ seizing
- ○ pinching
- ○ grabbing
- ○ grasping
- ○ …………



2. SENSORIAL LEVEL

3 →

How would you describe the material?

	2	-1	0	1	2	
hard	[✓ ○]	○	○	○	○	soft
smooth	○	○	[✓ ○]	○	○	rough
matte	[✓ ○]	○	○	○	○	glossy
not reflective	[✓ ○]	○	○	○	○	reflective
cold	○	○	[✓ ○]	○	○	warm
not elastic	[✓ ○]	○	○	○	○	elastic
opaque	[✓ ○]	○	○	○	○	transparent
tough	○	○	○	[✓ ○]	○	ductile
strong	○	[✓ ○]	○	○	○	weak
light	[✓ ○]	○	○	○	○	heavy
regular texture	○	○	[✓ ○]	○	○	irregular texture
fibred	○	[✓ ○]	○	○	○	not-fibred

4. INTERPRETIVE LEVEL

What do you associate with the material?

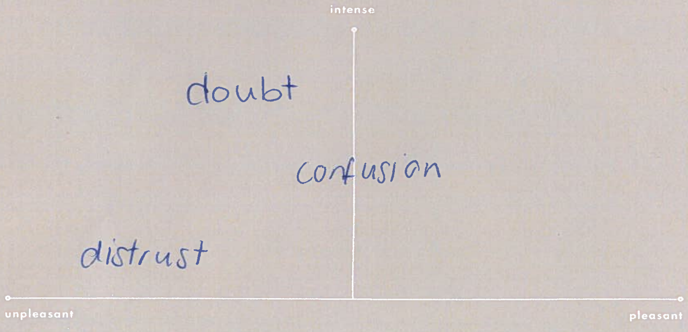
How would you describe it?

meaning 1	meaning 2	meaning 3
natural	Strange	Sober
-kleur	-hard product (non-elastic) but soft surface	~~-colour~~ -kleur is niet erg opvallend

↓ 5 (unfold the map and open sidewings)

3. AFFECTIVE LEVEL

What emotions does the material elict?



← 4

5. FINAL REFLECTIONS

Why do you think the material is..?

What is the most pleasant quality of the material?

hard

What is the most disturbing quality of the material?

No elestacity, ineens breekt het

What is the most unique quality of the material?

Soft surface

17

EXPERIENTIAL CHARACTERIZATION MAP

This map aims to support you in understanding how people experience materials.

start →

1. PERFORMATIVE LEVEL

What does the material make you do? 2 →

How do you touch the material?

- ○ pressing
- [✓ rubbing]
- ○ grazing
- [✓ compressing]
- ○ poking
- ○ caressing
- ○ fiddling
- ☒ pounding
- ○ pushing
- [✓ knoching]

How do you move the material?

- ○ folding
- ○ lifting
- ○ weighing
- [✓ bending]
- ○ flexing
- ○ picking
- ○ squeezing
- [✓ smelling]

How do you hold the material

- [✓ holding]
- ○ seizing
- ○ pinching
- ○ grabbing
- ○ grasping
- ○ ....

2. SENSORIAL LEVEL

3 →

How would you describe the material?

	-2	-1	0	1	2	
hard	○	○	○	○●	○	soft
smooth	○●	○	○	○	○	rough
matte	●	○	○	○	○	glossy
not reflective	●	○	○	○	○	reflective
cold	○	○	○	●	○	warm
not elastic	○	○	●	○	○	elastic
opaque	●	○	○	○	○	transparent
tough	○	○	●	○	○	ductile
strong	○	○	○	●	○	weak
light	●	○	○	○	○	heavy
regular texture	○	○	○	●	○	irregular texture
fibred	○	○	○	○	●	not-fibred

4. INTERPRETIVE LEVEL

What do you associate with the material?

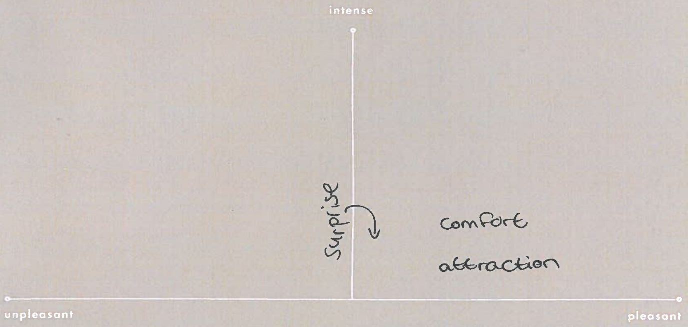
How would you describe it?

meaning 1	meaning 2	meaning 3
cosy	Elegant	~~Sober~~/natural
• Niet strak • kleur	• mat • Bijzondere textuur	• Natuur is niet strak

↓ 5 (unfold the map and open sidewings)

3. AFFECTIVE LEVEL

What emotions does the material elict?



← 4

5. FINAL REFLECTIONS

Why do you think the material is...?

What is the most pleasant quality of the material?

Feel

What is the most disturbing quality of the material?

Hij verkleurt

What is the most unique quality of the material?

Powdery feel

18

EXPERIENTIAL CHARACTERIZATION MAP

This map aims to support you in understanding how people experience materials.

start →

1. PERFORMATIVE LEVEL

What does the material make you do? 2 →

How do you touch the material?

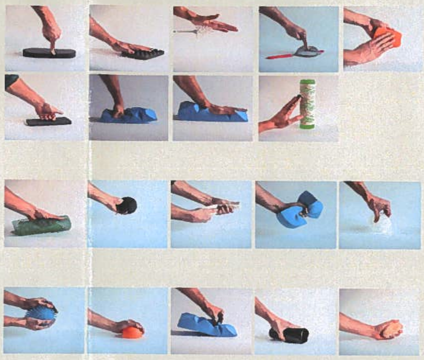
- ○ pressing
- [✓ rubbing]
- ○ grazing
- [✓ compressing]
- ○ poking
- ○ caressing
- ○ fiddling
- ○ pounding
- ○ pushing
- ○ ....

How do you move the material?

- ○ folding
- ○ lifting
- ○ weighing
- ○ bending
- [✓ turning]
- ○ flexing
- ○ picking
- ○ squeezing
- ○ smelling

How do you hold the material

- [✓ holding]
- ○ seizing
- ○ pinching
- ○ grabbing
- ○ grasping
- ○ ....



2. SENSORIAL LEVEL

3 →

How would you describe the material?

	-2	1	0	1	2	
hard	○	○	○	[✓ ○]	○	soft
smooth	○	[✓ ○]	○	○	○	rough
matte	[✓ ○]	○	○	○	○	glossy
not reflective	[✓ ○]	○	○	○	○	reflective
cold	○	○	○	[✓ ○]	○	warm
not elastic	[✓ ○]	○	○	○	○	elastic
opaque	[✓ ○]	○	○	○	○	transparent
tough	[✓ ○]	○	○	○	○	ductile
strong	○	○	○	○	[✓ ○]	weak
light	○	[✓ ○]	○	○	○	heavy
regular texture	○	○	○	[✓ ○]	○	irregular texture
fibred	○	○	○	○	[✓ ○]	not-fibred

4. INTERPRETIVE LEVEL

What do you associate with the material?

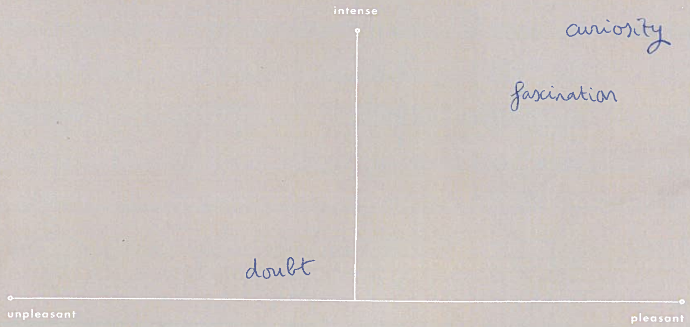
How would you describe it?

meaning 1	meaning 2	meaning 3
hand crafted	natural	~~sober~~ calm
gypsum / clay feel, reminds me of childhood	colour and layers remind of nature mushrooms	smooth surface

↓ 5 (unfold the map and open sidewings)

3. AFFECTIVE LEVEL

What emotions does the material elict?



← 4

5. FINAL REFLECTIONS

Why do you think the material is...?

What is the most pleasant quality of the material?

~~organic shape~~ smooth surface

What is the most disturbing quality of the material?

colour difference

What is the most unique quality of the material?

wall thickness difference

19

EXPERIENTIAL CHARACTERIZATION MAP

This map aims to support you in understanding how people experience materials.

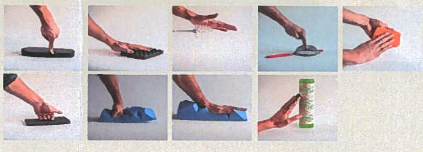
start →

1 PERFORMATIVE LEVEL

What does the material make you do? 2 →

How do you touch the material?

● pressing
● rubbing
○ grazing
● compressing
○ poking
● caressing
○ fiddling
○ pounding
○ pushing
○ …………



How do you move the material?

○ folding
● lifting
○ weighing
● bending
○ flexing
○ picking
○ squeezing
○ smelling

How do you hold the material

● holding
○ seizing
○ pinching
● grabbing
○ grasping
○ …………

2. SENSORIAL LEVEL

3 →

How would you describe the material?

	-2	-1	0	1	2	
hard	○	●	○	○	○	soft
smooth	☒	○	○	○	●	rough
matte	●	○	○	○	○	glossy
not reflective	●	○	○	○	○	reflective
cold	●	○	○	○	○	warm
not elastic	●	○	○	○	○	elastic
opaque	●	○	○	○	○	transparent
tough	●	○	○	○	○	ductile
strong	○	○	○	●	○	weak
light	●	○	○	○	○	heavy
regular texture	○	○	○	○	●	irregular texture
fibred	○	○	○	●	○	not-fibred

4. INTERPRETIVE LEVEL

What do you associate with the material?

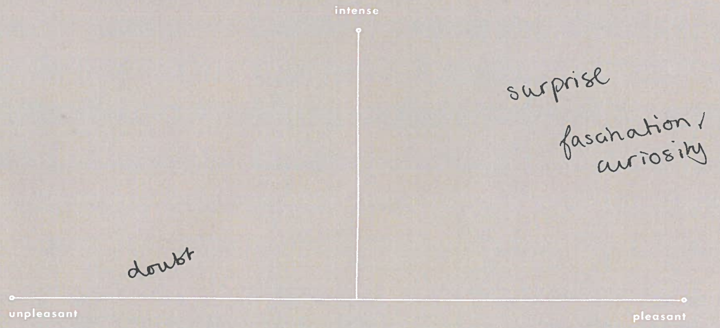
How would you describe it?

meaning 1	meaning 2	meaning 3
hand crafted	sober	not sexy
imperfections ~~one~~ layers 3D print bobbels	color ~~kleur~~ matte cement-like	- 3D printer - opposite apple commercial -messy -

↓ 5 (unfold the map and open sidewings)

3. AFFECTIVE LEVEL

What emotions does the material elict?



← 4

5. FINAL REFLECTIONS

Why do you think the material is..?

What is the most pleasant quality of the material?

blobs

What is the most disturbing quality of the material?

cracks

What is the most unique quality of the material?

type of material in combination with manuf. method seems mismatch in a nice way

---

20

EXPERIENTIAL CHARACTERIZATION MAP

This map aims to support you in understanding how people experience materials.

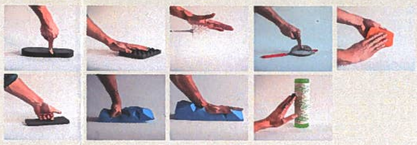
start →

1 PERFORMATIVE LEVEL

What does the material make you do? 2 →

How do you touch the material?

● pressing
● rubbing
○ grazing
● compressing
○ poking
● caressing
○ fiddling
● pounding
○ pushing
○ …………



How do you move the material?

○ folding
● lifting
○ weighing
● bending
● Knocking
○ flexing
○ picking
○ squeezing
○ smelling
● Turning

How do you hold the material

● holding
○ seizing
○ pinching
○ grabbing
○ grasping
○ …………

2. SENSORIAL LEVEL

3 →

How would you describe the material?

	-2	-1	0	1	2	
hard	●	○	○	○	○	soft
smooth	○	●	○	○	○	rough
matte	●	○	○	○	○	glossy
not reflective	●	○	○	○	○	reflective
cold	○	○	●	○	○	warm
not elastic	●	○	○	○	○	elastic
opaque	●	○	○	○	○	transparent
tough	●	○	○	○	○	ductile
strong	○	○	○	○	●	weak
light	●	○	○	○	○	heavy
regular texture	○	○	●	○	○	irregular texture
fibred	○	●	○	○	○	not-fibred

4. INTERPRETIVE LEVEL

What do you associate with the material?

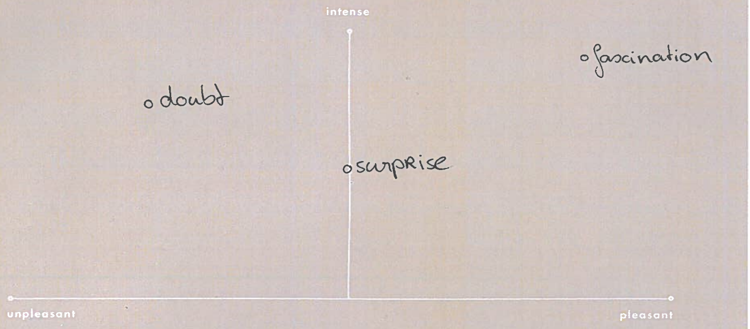
How would you describe it?

meaning 1	meaning 2	meaning 3
hand-crafted	not sexy	natural
3D-printing; but the material is normally hand-crafted	'droopy' layers imperfections	clay / earthwork earthy colour

↓ 5 (unfold the map and open sidewings)

3. AFFECTIVE LEVEL

What emotions does the material elict?



← 4

5. FINAL REFLECTIONS

Why do you think the material is..?

What is the most pleasant quality of the material?

'Earthy' → clay-like

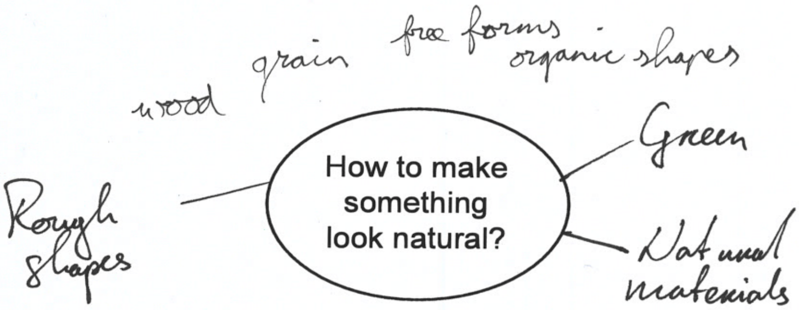
What is the most disturbing quality of the material?

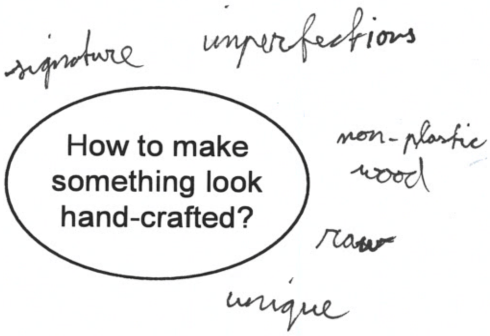
non-uniform layer-thickness

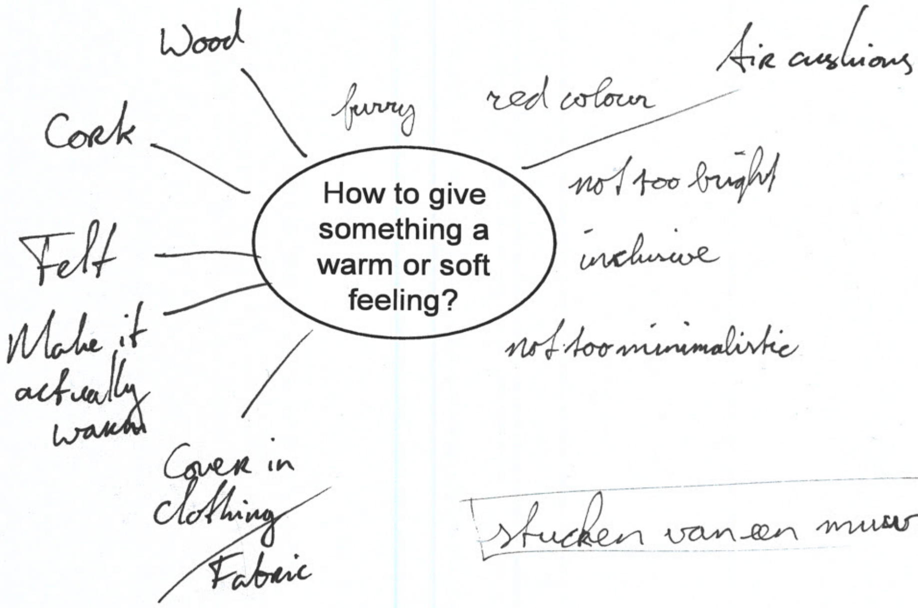
What is the most unique quality of the material?

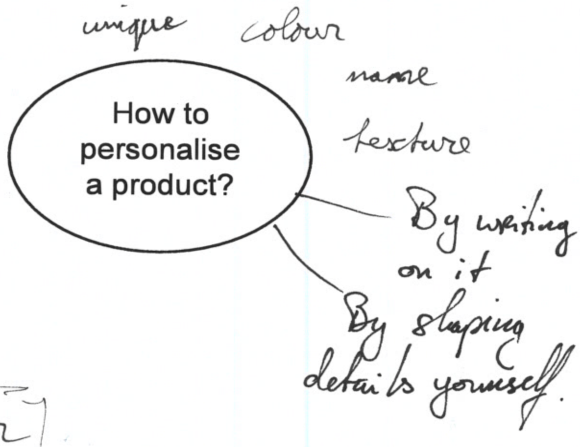
Light-weight

Appendix 6:
Brainstorms in groups (brainwriting & brain drawing)

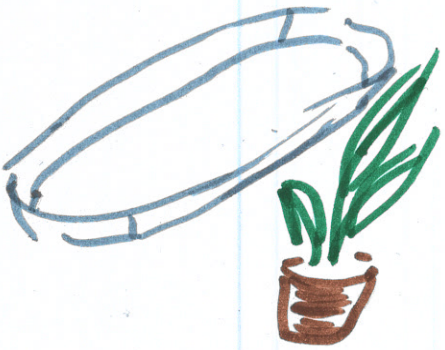

How to make something look natural?

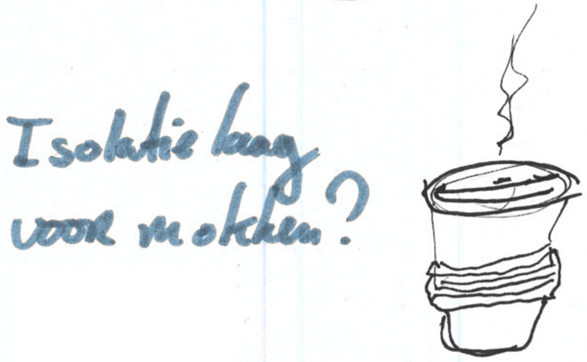

How to make something look hand-crafted?

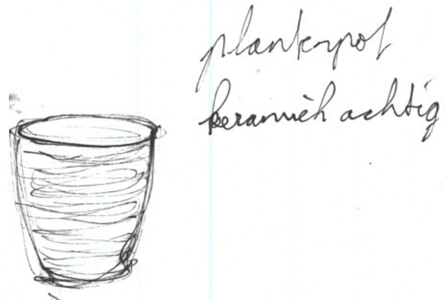

How to give something a warm or soft feeling?


How to personalise a product?

stucken van een muur







How to make something look strong or fragile?

- Make it thick or thin
- Make it transparant or solid
- Make it look brittle
- Make it look structurally sound or bad.
- material
  - plastic - fragile
  - metal - strong

How to use rough textures/ imperfections?

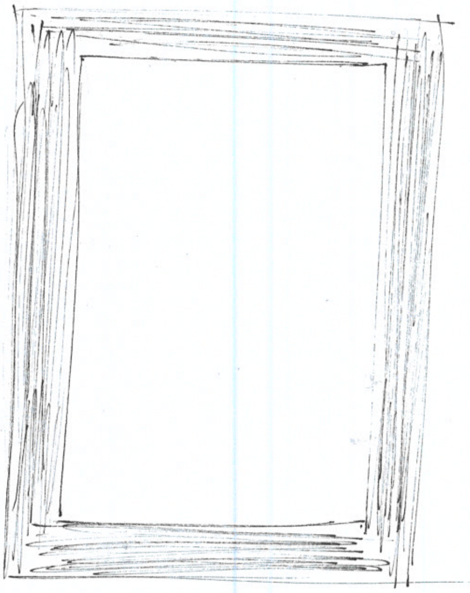
- For grip
- For teaming
- For aesthetics
- To communicate life lessons → Nothing is perfect
- For grinding
- For sanding

How to reduce weight?

- Topology Optimisation
- lighter material
- reduce components

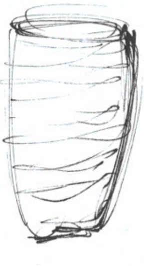
How to dissolve or recycle a material?

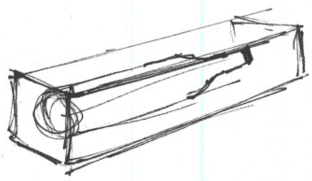
- easily ~~sep~~ seperable
- In acid
- In nature
- By breaking it down
- Make it modular
- give it a different use.



picture frame

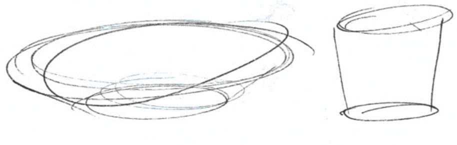
wijn koeler / doos

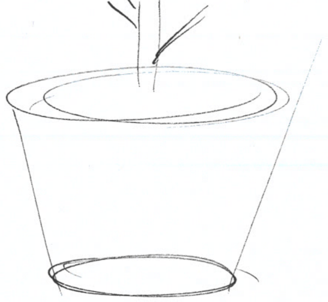


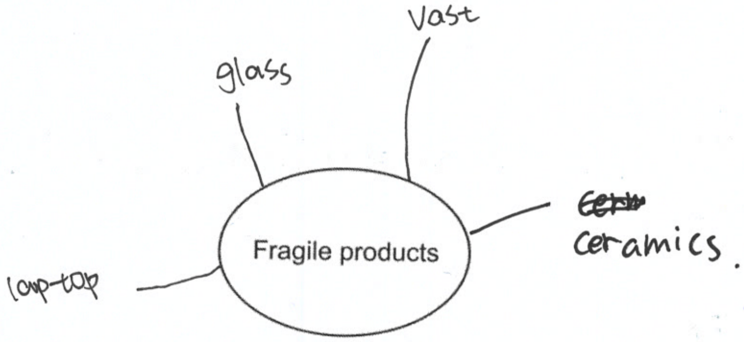


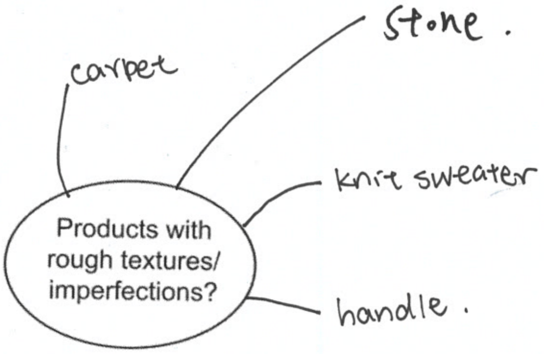
Protecting Steel beams in buildings

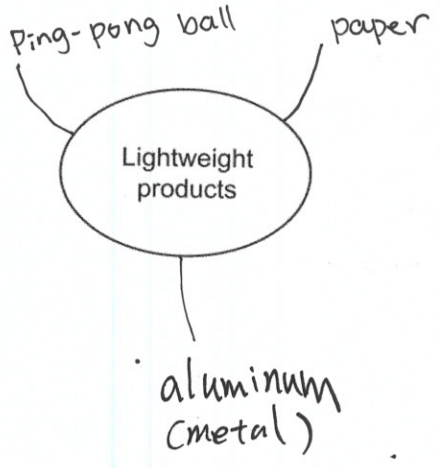
KITCHEN
CERAMICS



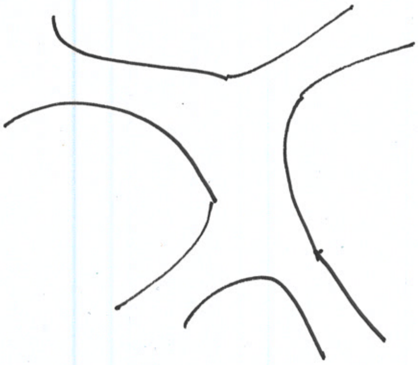




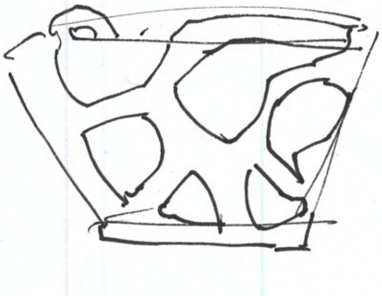




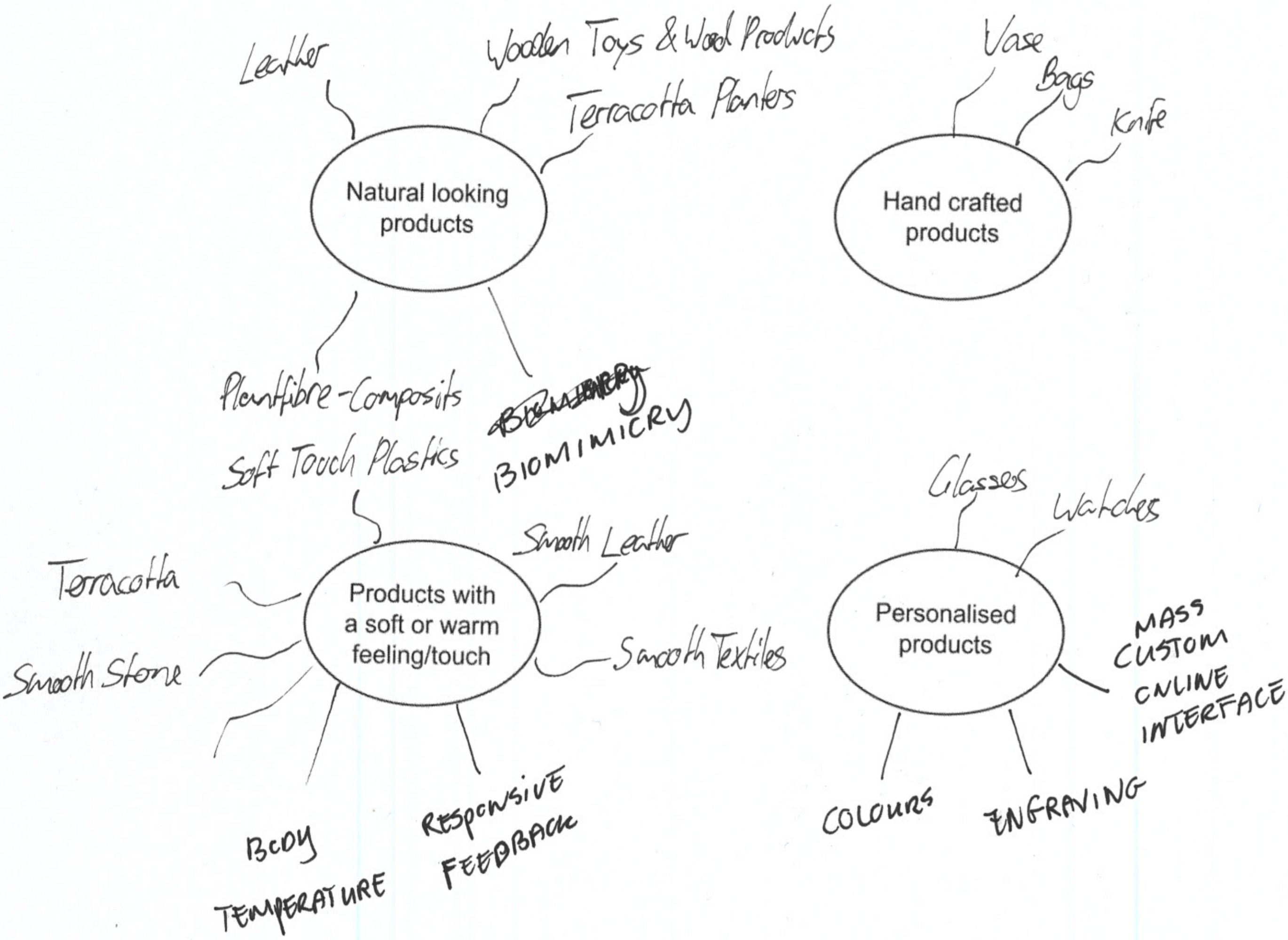
①

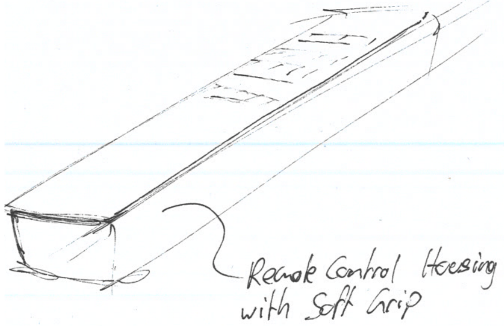


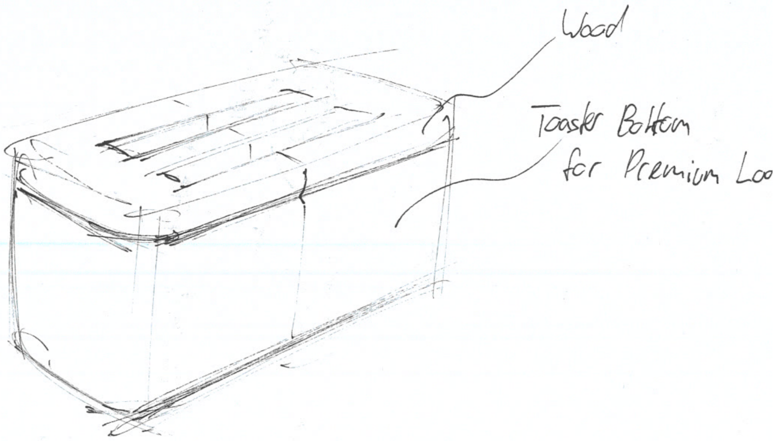
② . For mug . (Some 3nterestin

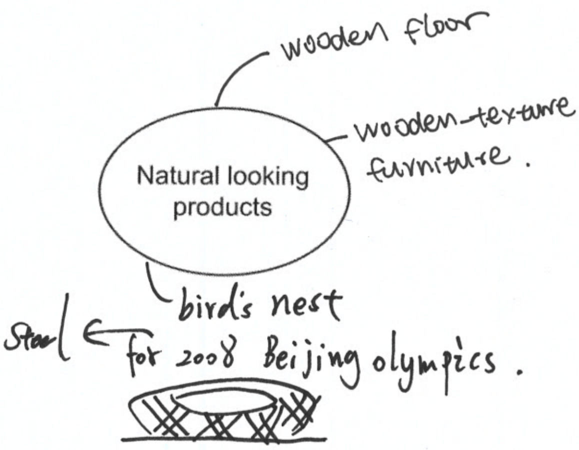


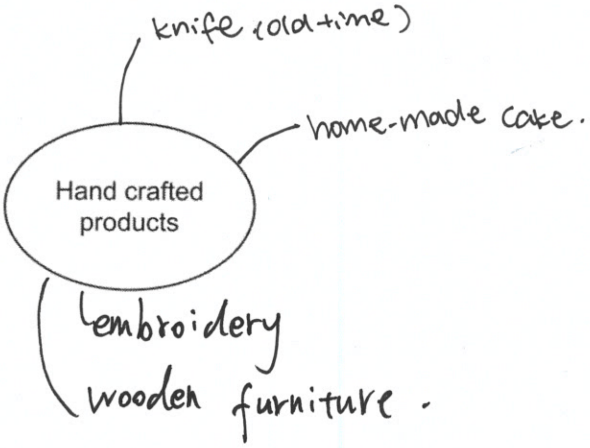
③ gardening tools .

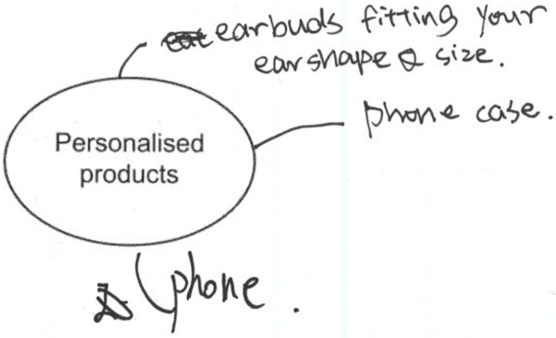

Leather
Wooden Toys & Wood Products
Terracotta Planters
Natural looking products
Plantfibre-Composits
~~Biomimicry~~
BIOMIMICRY
Vase
Bags
Knife
Hand crafted products
Soft Touch Plastics
Terracotta
Smooth Leather
Products with a soft or warm feeling/touch
Smooth Stone
Smooth Textiles
BODY TEMPERATURE
RESPONSIVE FEEDBACK
Glasses
Watches
Personalised products
MASS CUSTOM
ONLINE INTERFACE
COLOURS
ENGRAVING

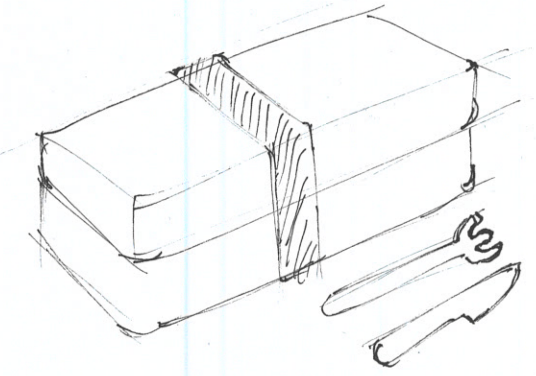

Remote Control Housing with Soft Grip


Wood
Toaster Bottom for Premium Loo

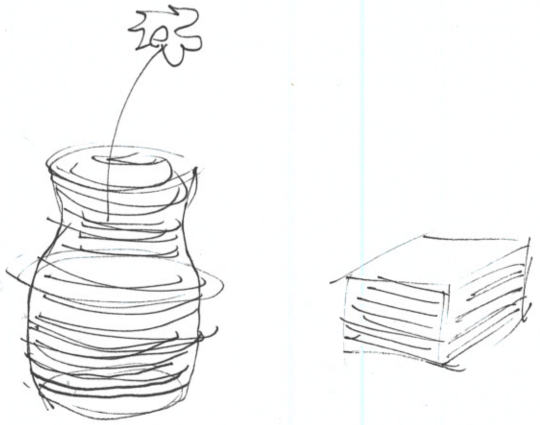








Lunch box & cutlery. (when you need to bring food somewhere)



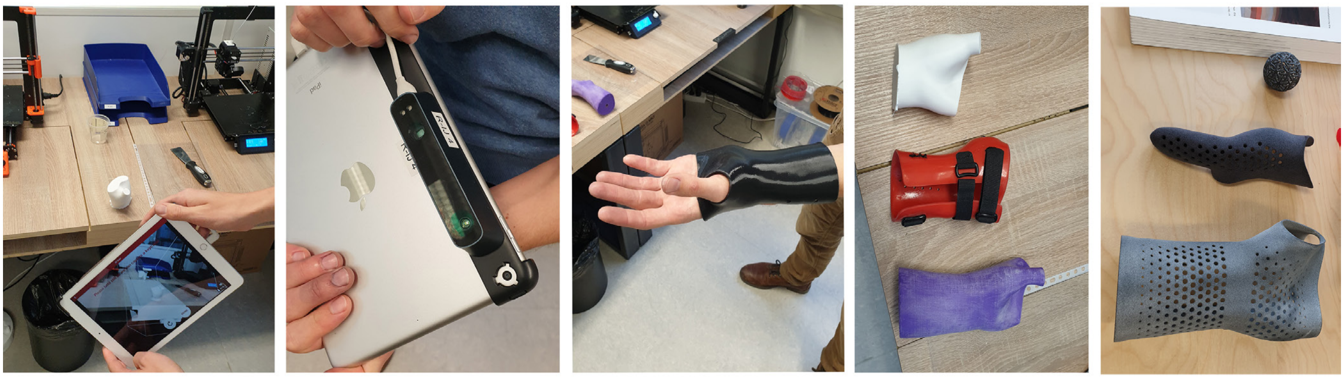
Home decoration + Storage.

Appendix 7:
Most suitable ideas

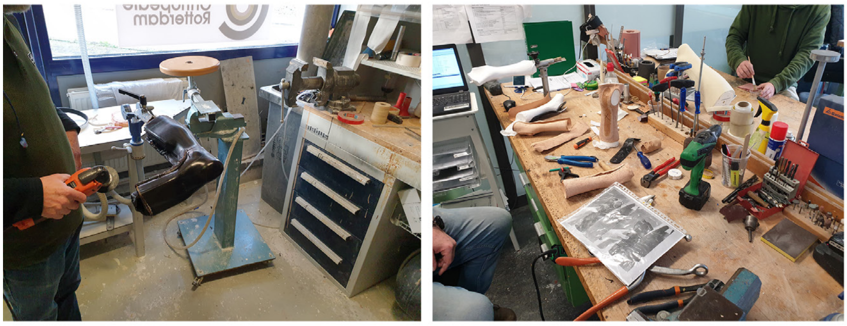
Idea	Matches with a CE	Matches with AM	Matches with this material
1. Circular gardening: A multifunctional flower pot for garden centers to replace for the old plastic flower pot inserts. After use as flower pot it can be put in another use, like toothbrush holder, cutlery holder or pen holder. When broken it can be returned to the garden center in return for another one, or for money.	-Re-use; product can be put in another use, and therefore the product can be used longer. -The product replaces plastic pots, so it diminishes plastic waste as well. -When broken the product is returned to the garden center/store, and a new cycle begins.	-To increase the chance of garden centers and customers to like this pot, AM is used to give it an appealing look which is only possible with AM. -AM can be used to make a flower pot plant-specific, so use the thickness and structures for a specific amount of water, feeding, licht and oxygen. -Clients are able to design their own flower pot and send the design to the garden centers.	-This crosslinked material gets flexible when wet, but does not dissolve. However, water enters the material. Since calcium carbonate is used as soil fertilizer, nutrients return to the flowers roots. -When too much water is given, the unused water enters the material and it evaporates from the outside, so the roots will not rot. When the earth is dry the water can return. -The other uses of the pot needs cleaning, which also needs a water resistant material. -Because it is water resistant the pot can be used outside as well. -The material has a natural and ceramic association, which matches with a flower pot.
2. Knife block & knife handle	-	-AM matches with the organic shape of knife handles. -A handle can be made which fits perfectly in somebody's hand.	-The holder can be used as knife sharpener because of the texture of the material. -The handle uses the soft touch of the material. -The knive can be washed because of the crosslinking.
3. Salt & pepper set The material is used to keep the salt, pepper and other herbs dry.	-When one of the 2 is broken, only one has to be reprinted. -When sold in a supermarket it can replaces the plastic packaging of salt and pepper sets.	-As an extra service stores/supermarkets can let you design your own salt and pepper set.	-The material absorbs the water from the salt or pepper. This keeps it dry. No added rice is needed. -The outside can be cleaned without the material dissolves. -The soft touch of the material makes the use pleasant.
4. 3D print support	-The material replaces plastic support, which normally is discarded after use.	-It will be used in 3D printers with two nozzles	-Support can be washed away which matches with the solubility of the non-crosslinked material.
5. Personalised Chess (or other toys)	-Plastic replacement since a lot of toys are made with plastic -When a part is broken, only one has to be reprinted to complete the set again.	-AM can be used to print personalized chess stones. -AM can be used to design dutch/zeeland themed toys as tourist products.	-The soft touch of the material matches with toys. -Cross linking; does not dissolve when child tries to eat/lick it and the stones are possible to clean.
6. Bottle vase A carafe which also can be used as a vase.	-Re-use; product can be put in another use, and therefore people want to use the product longer.	-Restaurants or hotels can make there own designs.	-The natural look of the material matches the application.
7. Cups & theepot	-	-	-The material isolates the heat. -The material needs to be very water resistant for this application.
8. Customizable coasters For example pancoasters, teapot coasters or cup coasters.	-When the restaurant buys a 3D printer it can recycle it’s own material.	-AM can be used to integrate a companies logo in the middle of the coaster.	-The material isolates the heat from the table surface. -When spilling water the coaster does not dissolve. -The coaster can be cleaned since the material is crosslinked and thus water resistant. -The soft material does not make scratches on tables.
9. Patient-specific braces A 3d printed braces which helps to recover a broken arm.	- The brace exists of 2 parts in order to get it around your arm. When it is broken by accident you only have to repair the broken part.	-The brace has holes so the arm does not get sweaty and itchy. -A custom made size and form is needed since everybodies arm is different.	-The material is water resistant so you can take a shower or walk through rain with it -When the arm is recovered the brace can be broken and the material can be recycled, or it gets de-crosslinked and it can be washed of. -The soft touch of the material is pleasant on the skin. -The low weight of the material is beneficial for something which has to be carried around all day.

Appendix 8:
Pictures orthopedic centre Rotterdam

The first notable thing was that not everything was hand made. For some simple injuries purchased universal materials were used, some of them for the production process of more difficult orthoses.



For other purposes, mostly medium difficult injuries, 3D printers are being used. An advanced 3D scanner, or a more simple one on the back of a tablet, scans a patients hand. This file gets digitally optimized and then sent to the Ultimaker. Different sorts of plastics were used, based on the injury. The red splint in the picture, for exmple, is flexible.

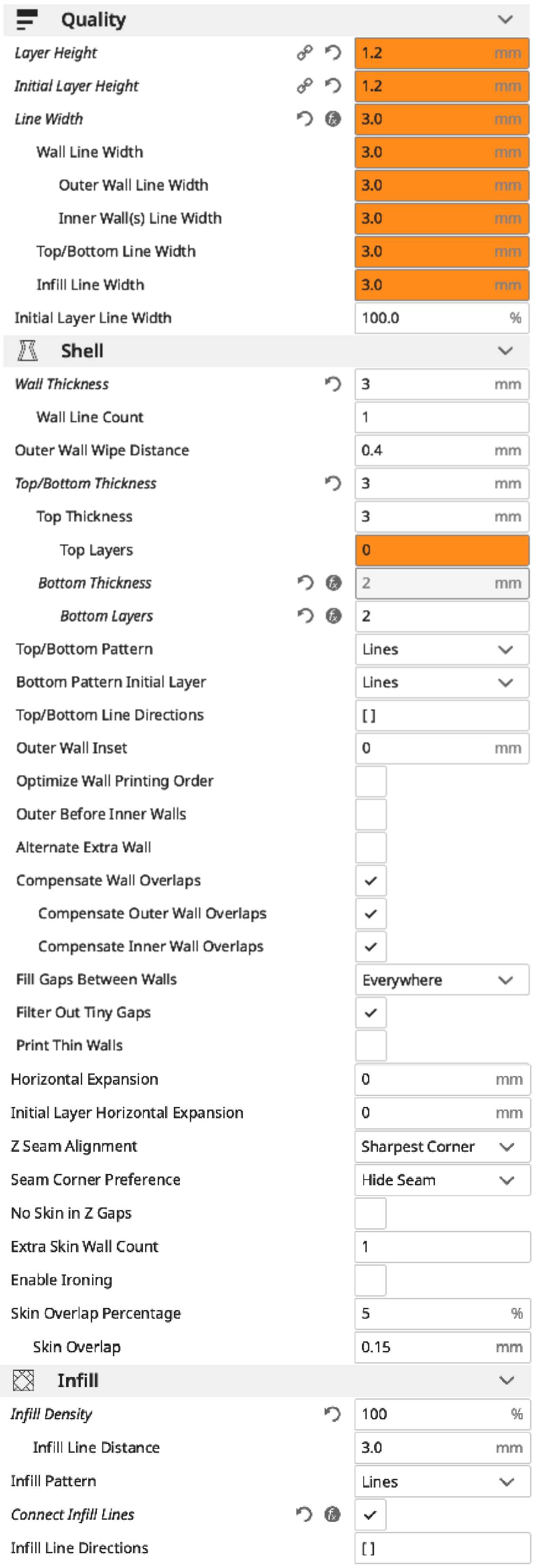


The most difficult orthoses, however, are still hand made. These are usually the bigger ones which needs to be worn for a longer period of time.

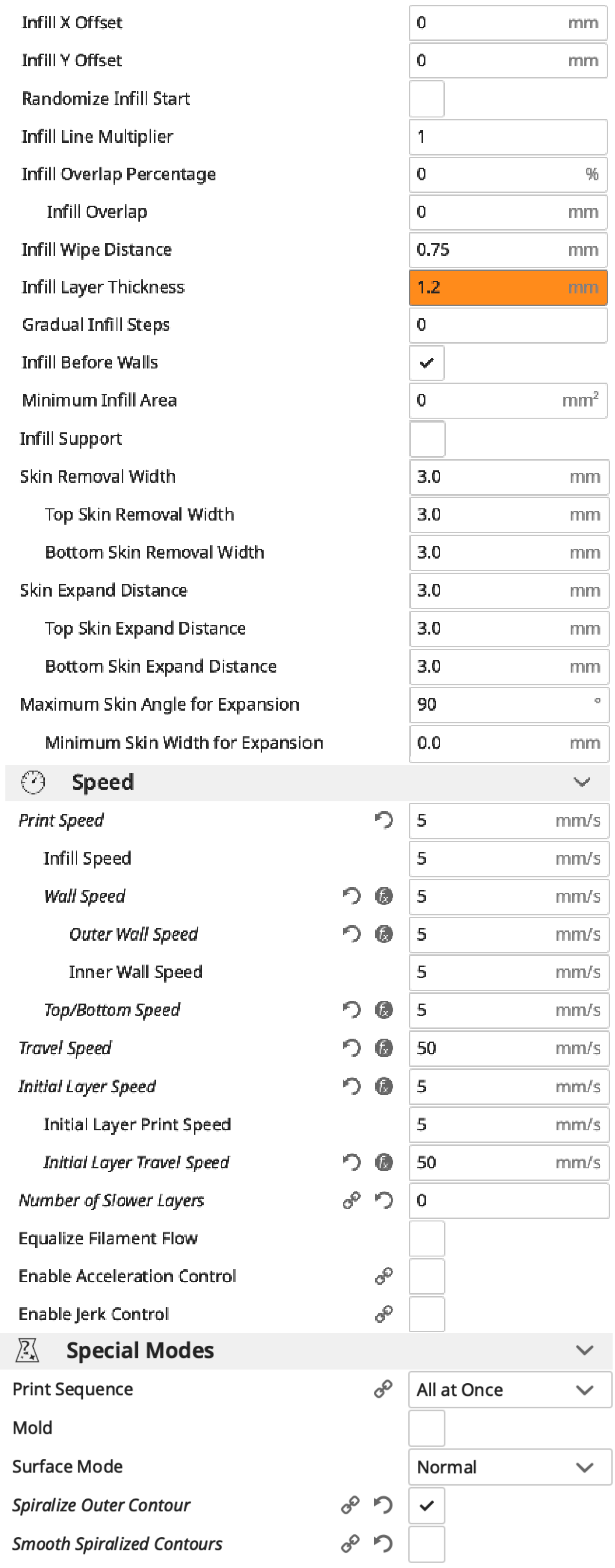
Wybren explained that 3D printed flexible splits have bending issues around the thumb.

To create these bigger orthoses, a 3D scan or fiber was used to create a negative mould of an arm. This negative mold was filled with gypsum to create the positive mold. On this positive mold the detailed orthoses from the pictures above were created.

Appendix 9:
Cura settings

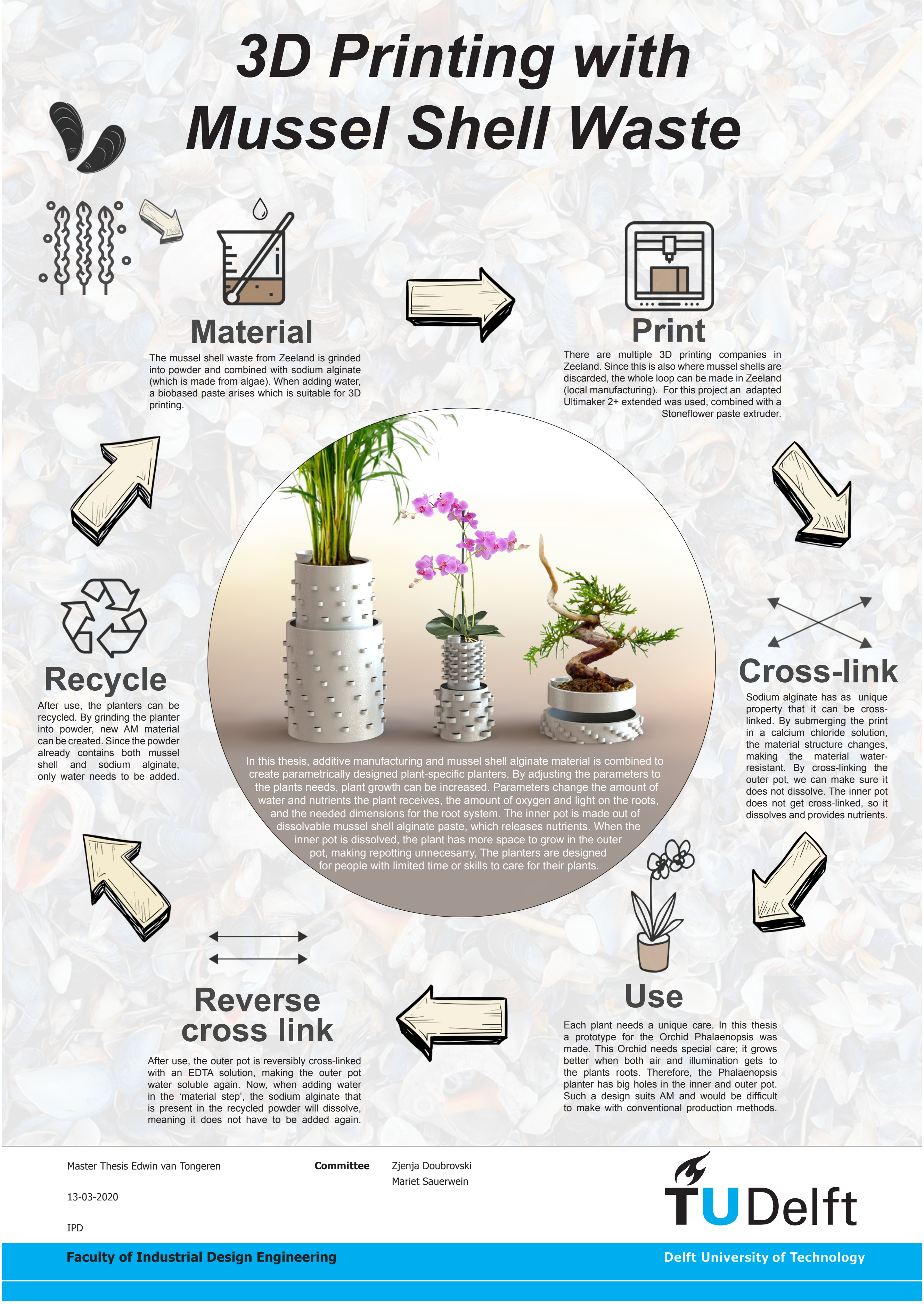


Quality	
Layer Height	1.2 mm
Initial Layer Height	1.2 mm
Line Width	3.0 mm
Wall Line Width	3.0 mm
Outer Wall Line Width	3.0 mm
Inner Wall(s) Line Width	3.0 mm
Top/Bottom Line Width	3.0 mm
Infill Line Width	3.0 mm
Initial Layer Line Width	100.0 %
Shell	
Wall Thickness	3 mm
Wall Line Count	1
Outer Wall Wipe Distance	0.4 mm
Top/Bottom Thickness	3 mm
Top Thickness	3 mm
Top Layers	0
Bottom Thickness	2 mm
Bottom Layers	2
Top/Bottom Pattern	Lines
Bottom Pattern Initial Layer	Lines
Top/Bottom Line Directions	[ ]
Outer Wall Inset	0 mm
Optimize Wall Printing Order	☐
Outer Before Inner Walls	☐
Alternate Extra Wall	☐
Compensate Wall Overlaps	☑
Compensate Outer Wall Overlaps	☑
Compensate Inner Wall Overlaps	☑
Fill Gaps Between Walls	Everywhere
Filter Out Tiny Gaps	☑
Print Thin Walls	☐
Horizontal Expansion	0 mm
Initial Layer Horizontal Expansion	0 mm
Z Seam Alignment	Sharpest Corner
Seam Corner Preference	Hide Seam
No Skin in Z Gaps	☐
Extra Skin Wall Count	1
Enable Ironing	☐
Skin Overlap Percentage	5 %
Skin Overlap	0.15 mm
Infill	
Infill Density	100 %
Infill Line Distance	3.0 mm
Infill Pattern	Lines
Connect Infill Lines	☑
Infill Line Directions	[ ]



Infill X Offset	0 mm
Infill Y Offset	0 mm
Randomize Infill Start	☐
Infill Line Multiplier	1
Infill Overlap Percentage	0 %
Infill Overlap	0 mm
Infill Wipe Distance	0.75 mm
Infill Layer Thickness	1.2 mm
Gradual Infill Steps	0
Infill Before Walls	☑
Minimum Infill Area	0 mm^2
Infill Support	☐
Skin Removal Width	3.0 mm
Top Skin Removal Width	3.0 mm
Bottom Skin Removal Width	3.0 mm
Skin Expand Distance	3.0 mm
Top Skin Expand Distance	3.0 mm
Bottom Skin Expand Distance	3.0 mm
Maximum Skin Angle for Expansion	90 °
Minimum Skin Width for Expansion	0.0 mm
Speed	
Print Speed	5 mm/s
Infill Speed	5 mm/s
Wall Speed	5 mm/s
Outer Wall Speed	5 mm/s
Inner Wall Speed	5 mm/s
Top/Bottom Speed	5 mm/s
Travel Speed	50 mm/s
Initial Layer Speed	5 mm/s
Initial Layer Print Speed	5 mm/s
Initial Layer Travel Speed	50 mm/s
Number of Slower Layers	0
Equalize Filament Flow	☐
Enable Acceleration Control	☐
Enable Jerk Control	☐
Special Modes	
Print Sequence	All at Once
Mold	☐
Surface Mode	Normal
Spiralize Outer Contour	☑
Smooth Spiralized Contours	☐

Appendix 10:
Poster for showcase



3D Printing with Mussel Shell Waste

Material

The mussel shell waste from Zeeland is grinded into powder and combined with sodium alginate (which is made from algae). When adding water, a biobased paste arises which is suitable for 3D printing.

Print

There are multiple 3D printing companies in Zeeland. Since this is also where mussel shells are discarded, the whole loop can be made in Zeeland (local manufacturing). For this project an adapted Ultimaker 2+ extended was used, combined with a Stoneflower paste extruder.

Cross-link

Sodium alginate has as unique property that it can be cross-linked. By submerging the print in a calcium chloride solution, the material structure changes, making the material water-resistant. By cross-linking the outer pot, we can make sure it does not dissolve. The inner pot does not get cross-linked, so it dissolves and provides nutrients.

Use

Each plant needs a unique care. In this thesis a prototype for the Orchid Phalaenopsis was made. This Orchid needs special care; it grows better when both air and illumination gets to the plants roots. Therefore, the Phalaenopsis planter has big holes in the inner and outer pot. Such a design suits AM and would be difficult to make with conventional production methods.

Reverse cross link

After use, the outer pot is reversibly cross-linked with an EDTA solution, making the outer pot water soluble again. Now, when adding water in the 'material step', the sodium alginate that is present in the recycled powder will dissolve, meaning it does not have to be added again.

Recycle

After use, the planters can be recycled. By grinding the planter into powder, new AM material can be created. Since the powder already contains both mussel shell and sodium alginate, only water needs to be added.

In this thesis, additive manufacturing and mussel shell alginate material is combined to create parametrically designed plant-specific planters. By adjusting the parameters to the plants needs, plant growth can be increased. Parameters change the amount of water and nutrients the plant receives, the amount of oxygen and light on the roots, and the needed dimensions for the root system. The inner pot is made out of dissolvable mussel shell alginate paste, which releases nutrients. When the inner pot is dissolved, the plant has more space to grow in the outer pot, making repotting unnecesarry, The planters are designed for people with limited time or skills to care for their plants.

Master Thesis Edwin van Tongeren

13-03-2020

IPD

Committee Zjenja Doubrovski
Mariet Sauerwein

TU Delft

Faculty of Industrial Design Engineering

Delft University of Technology