Graduation Report Kirsten Lussenburg 2014

Data · November 2014

5 authors, including:

Kirsten Lussenburg
Delft University of Technology

Jo Geraedts
Delft University of Technology

Elvin Karana
Delft University of Technology

Zjenja Doubrovski
Delft University of Technology

DESIGNING [WITH] 3D PRINTED TEXTILES

A MATERIAL DRIVEN DESIGN PROJECT

MASTER THESIS
KIRSTEN LUSSENBURG

COLOPHON

Master thesis
MSc. Intergrated Product Design
09 September 2014

Faculty of Industrial Design Engineering
Delft University of Technology
The Netherlands

Kirsten Lussenburg
kirsten_m_l@hotmail.com
Student number: 1376373

Official chair of supervisory team: Dr. E. Karana
Substitute chair: Prof. dr. ir. J. Geraedts

TU Delft mentor: Ir. E. L. Doubrovski

External mentor: Ir. N. M. van der Velden

ACKNOWLEDGEMENTS

First, a word of thanks to everyone who has supported me during this project. I would like to thank all members of my supervisory team for their advice and guidance along the way. I want to thank Elvin Karana, first of all for giving me the opportunity to work for her as a student assistant, but most importantly for teaching and supporting me throughout this project. I would like to thank Zjenja Doubrovski for always knowing how to fix the printers, Natascha van der Velden, for involving me in all her projects and for her enthusiasm and Jo Geraedts for taking over as my chair, even during his vacation. Finally, I want to thank all my friends and family for their support and not growing tired of me only talking about 3D printing. And special thanks to Jaap Haringa, for everything.

1. EXECUTIVE SUMMARY

This master thesis is the result of a graduation project for the master Integrated Product Design the faculty of Industrial Design Engineering, Delft University of Technology. The title of this thesis is Designing [with] 3D Printed Textiles. The main assignment is to design a meaningful garment using 3D printed textiles.

The approach that was adopted for this project is a recently developed method on Material Driven Design (MDD), which suggests a number of steps to design meaningful products when a material is the departure point. As this method has not yet been applied on a project involving AM, another goal is to explore how the MDD method can be used in a project where AM is the primary production method.

3D printed textiles as a material category are influenced by material, structure and process (MSP), which cannot be seen apart from each other and influence each other. In order to gain an understanding of the MSP, a number of samples of 3D Printed textiles were obtained. Some samples were collected from AM service providers, designers, and open-source design databases, while others were specifically designed and 3D Printed for this project. It was found that different combinations of MSP result in different materials that can have different, meaningful applications in different contexts.

An analysis of traditional textiles found that flexibility is the most important property for textiles, since without flexibility no wearable garment can be produced. It is possible to divide textiles into four levels: garment, textile, yarn and fiber. Each level has a main structure, which results in a hierarchical structure for the overall material. This hierarchical structure is responsible for most of the mentioned properties that are desirable in textiles, such as flexibility, warmth, softness, and absorption. In order to obtain the same structure for 3D printed textiles, it is important to find a way to mimic this structure.

Since flexibility was found to be the most important property for textiles, a classification for 3D printed textiles is proposed based on the main source of the flexibility, i.e. the structure or the material. Structure-based refers to the fact that the flexibility is obtained purely by the application of an appropriate structure, regardless of the material used. This kind of flexibility is obtained by means of multiple assemblies. Material-based refers to the fact that the flexibility is obtained purely due to the characteristics of the material, by the use of flexible materials such as elastomers. Finally, an overlapping category can be distinguished which uses both material- and structure-based principles, named thin structures.

The experiential characteristics of 3D printed textiles were examined by means of a number of samples. The samples elicited movement in order to explore the flexibility of the material, by means of shaking, throwing and caressing the samples. 'Playfulness' and 'surprising' were found as pre-settled meanings, for which the flexibility of the material and the fact that they were 3D Printed contributed most. The latter also elicited a positive reaction, since the 3D Printing process is still perceived as new, exciting, and innovative.

A vision statement was created that described the interaction with the material. It was formulated as: *"I want people to have an attachment to their 3D Printed garment in order to extend its life span, by creating a personally engaging experience, like the act of blowing bubbles"*. 'Blowing bubbles' is used as a metaphor, illustrating a simple, engaging act that is familiar to everyone. Making the biggest bubbles is a challenge, and watching the light react on them is a pleasure; they are engaging to make and engaging to watch. Two meanings were distilled from this metaphor: intriguing and familiar, The meaning intriguing is related to the engaging experience, which will keep being interesting and surprising over time, while the meaning familiar can be described as 'a friendly relationship based on frequent association', comparable to a favourite jeans that has been worn many times.

These meanings were translated to material qualities, which form the requirements for the new material together with the requirements found from the context analysis. On a material level, the 3D Printed textile should be suitable for use in garments, and thereby withstand a number of technical requirements, such as flexibility, tear resistance, breathability and water resistance. There are also a number of experiential qualities for the material that are related to creating a textile that is comfortable to use. Softness, smoothness, warmth, lustre and coarseness are examples of these qualities.

One of the tested MSP's was thought to be most suitable for use as a textile and its fit to the vision. However, for this MSP the structure and process were found appropriate, the material was not suited for use as a textile. Therefore, a number of experiments were conducted with different materials. The material that showed the best results and had the best fit with the intended vision was a mixture of cellulose fibers with a flexible acrylic. Although this material is not suitable for 3D printing yet, it does give an impression of what the material should be like in the future.

A concept was developed using this MSP. In order to do so, the unique properties of the MSP were analysed: its aesthetics are most prevalent, most notably the pattern that resembles lace and is somewhat prevailing. It is also very suitable to produce property gradients (i.e. making the pattern smaller and higher decreases the flexibility of the material), therefore it makes sense to use it for applications where this quality could be used to the fullest. By means of several brainstorm sessions, the most valuable product direction was found to be bras, since they have a combination of supportive and comfort functions. The choice was made to design a corselet, in order to demonstrate the versatility of the selected MSP.

The fact that 3D Printing significantly reduces the number of process steps necessary and the amount of waste material, means it has the potential to contribute to environmental sustainability. The total impact of the product was evaluated by means of a Life Cycle Analysis (LCA), and compared to traditional manufactured textiles for 1 kg of textile. The results of the analysis were compared to those of traditional textiles, and it was found that the environmental impact of the 3D Printed textile is comparable to those of woven textiles with a yarn thickness of 300 dtex.

This thesis concludes with a large number of recommendations regarding the chosen MSP, product and future of 3D printed textiles.

2. TABLE OF CONTENTS

PART I: LITERATURE REVIEW

PART II: MATERIAL CHARACTERIZATION

PART III: MATERIALS EXPERIENCE PATTERNS

PART IV: MATERIAL & PRODUCT DESIGN

PART V: RECOMMENDATIONS & EVALUATION

APPENDICES

3. INTRODUCTION

3.1 INTRODUCTION

This master thesis is the result of a graduation project for the master Integrated Product Design at the faculty of Industrial Design Engineering, Delft University of Technology. The title of this thesis is Designing [with] 3D Printed Textiles. It describes the design process from a start as a material direction, to the material embodied in a product as an end result. This project is an example of a Material Driven Design process, in which 3D printed textiles form the main driver. The goal of this project is to apply a 3D printed textile to a meaningful product design. Additionally, this project will serve as an example how the Material Driven Design method can be applied in combination when a primary production method is established.

This thesis will give insight into the entire design process and the outcomes of the design project. This chapter will explain the research objectives, methodology and structure of this thesis.

3.2 RESEARCH OBJECTIVES

The goal of this thesis is to design a meaningful product using 3D printed textiles, by means of following the steps as suggested by the Material Driven Design method.

This project originated from the question whether 3D printing could serve as a sustainable replacement for current textile manufacturing processes. Although the focus has been shifted to the development of a meaningful 3D printed textile itself, it will still focus on the production of a material suitable for garments, which in this case refers to all products that are worn on or close to the body. Sustainable and environmental issues will serve as a red thread throughout this thesis, as a means to evaluate the developed materials.

A number of research questions are formulated in order to realize the assignment:

- What are 3D printed textiles?
- How do material, structure and process influence the properties of the resulting material?
- How does the user experience 3D printed textiles?
- What is the value of 3D printed textiles as compared to regular textiles?
- What is the environmental impact of 3D printed textiles?
- How can 3D printed textiles be used to produce a garment?
- What is the meaning of 3D printed textiles?

3.3 METHODOLOGY

A number of different methodologies have been used during this project. They are shortly discussed below.

3.3.1 MDD

For this project, a Material Driven Design (MDD) method was used (Karana et al., in review). The goal of this process is to facilitate product design for which a material is the main driver. The method first suggests developing a thorough understanding of the material, not only its technical properties, but also how the material is experienced by users, in order to reveal the unique qualities that can be emphasized in the final application.

Karana et al. present four main steps in the MDD Method, as shown in Figure 01. The first step is centred on gaining an understanding of the material, by performing both a technical characterization as well as an experiential characterization. These can often be performed simultaneously, as they will complement each other. An important part of this step is playing or 'tinkering' with the material, to explore its limits. In this case, since the material can be described as a "material proposal", as it is not yet fully developed, it is important to first understand what the material actually is, how it can be defined and what its boundaries are. By means of literature reviews, analysis of benchmark materials and experimentation, the limits of the material and its different forms have been discovered and classified.

Early in the research phase it was found that 3D printed textiles are not just a material, but their properties are influenced by a combination of material, structure and process (MSP). In order to distinguish between the use of the word material in the literal sense, and the use to refer to the combination of material, structure and process (i.e. the 3D printed textile), the latter will be called MSP in this thesis.

In the second step, a Materials Experience Vision is created. This vision expresses how a designer envisions the role of the material in product design, in relation to the user, product and context. The vision should be related to the unique functional and experiential qualities of the material, as well as to potential of the material for future, unforeseen applications.

Such an abstract vision can be hard to relate back to formal material qualities. Therefore, in the third step, the designer can analyse the vision in order to obtain meanings (e.g. high-tech, feminine, cosy, friendly) that can be translated to material properties using Meaning Driven Material Selection (MDMS) [Karana et al., 2008].

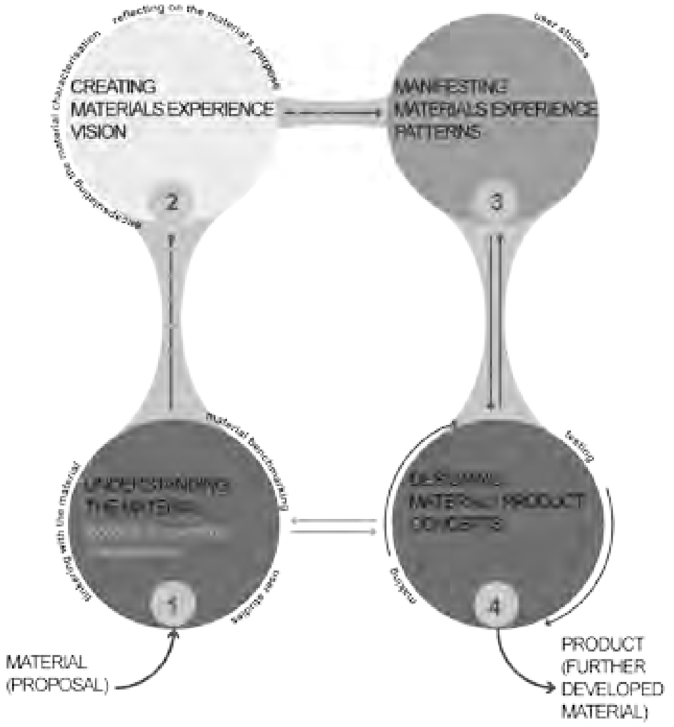


FIGURE 01. THE MATERIAL DRIVEN DESIGN METHOD [KARANA ET AL., IN REVIEW]

Finally, in the fourth step, the findings obtained in the previous steps are used to create material/product concepts. In this project, two workshops were given as a means to gain input for this step: one with fashion design students, and one with industrial design students.

The steps as described above can be followed consequently, but in practice it will be an iterative process.

3.3.2 MDMS

The Meaning Driven Material Selection (MDMS) method was developed by Karana et al. (2009) as an approach to explore the relationship between materials and meanings and to translate these into tangible material properties. In this method, a number of participants are asked to select a material that fits a specific meaning and answer a number of questions regarding this material. By analysing the response of the participants both qualitatively and quantitatively, the designer can get an idea as to what technical and sensorial properties attribute to that particular meaning. The results can be visualized in a Meanings of Materials (MoM) model (Figure 02), which incorporates the interactions between user, material and product. More on the MDMS method can be found in Karana et al. (2009).

3.3.3 LCA

The Life Cycle Analysis (LCA) is used to estimate the environmental impact of 3D printed textiles as compared to traditional textiles. In this method, eco-costs are used to compare different products/scenarios to each other for every step of the life cycle of a product. Eco-costs can be defined as the costs that are necessary to reduce the environmental impact to a level that the earth can sustain [Vogtländer, 2012]. Using eco-costs in the LCA provides a quick and transparent insight in the burden of each step of the product life cycle. More information on LCA can be found in Vogtländer (2012) or on www.ecocostvalue.com.

3.3.4 LITERATURE REVIEW

An extensive literature review was used to build a framework regarding additive manufacturing, textiles and 3D printed textiles, in order to map the state-of-the-art, technological developments, opportunities and boundaries for these fields. The literature review served as a theoretical framework across this thesis.

3.3.5 WORKSHOPS

Two workshops were organised in order to gain creative input: one with fashion design students, and one with industrial design students. The goal of the first workshop was to see how fashion designers can apply the possibilities of 3D printing and how they envision the role of 3D printing in fashion in the future. The goal of the second workshop was to find out how the students evaluated the MSP's based on a given meaning and how they used this to translate into meaningful product design. The workshops are more elaborately discussed in section 13.1 and 13.2 and Appendix H and I.

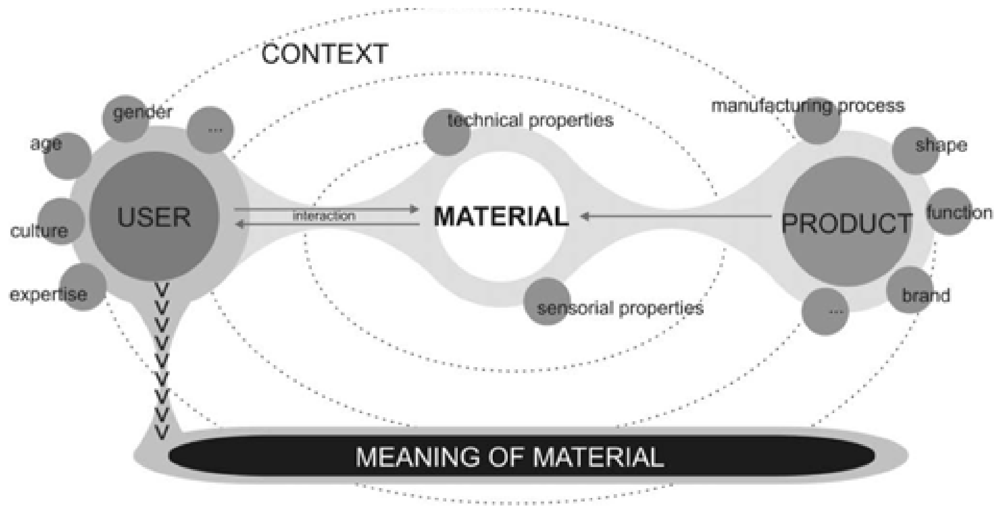


FIGURE 02. MEANINGS OF MATERIALS MODEL [KARANA ET AL., 2009]

3.4 READING GUIDE

This thesis is structured into five parts, each consisting of several chapters. The parts are clustered to contain the information that is related to each other.

This section indicates the content of the parts: which information can be found in the parts and the main research goals of the parts. Certain terminology and abbreviations have been collected in the glossary after the last part.

PART I: LITERATURE REVIEW

In this section, the main theoretical framework for the thesis is build. By means of literature research, the subjects of additive manufacturing, textiles and 3D printed textiles have been explored. The chapter on additive manufacturing discusses the main concept of the technology, the 3D printing processes that were used during this project, and concludes with a discussion of the factors that can contribute to the production of garments, and those that still need development.

The chapter on textiles explores the common materials and structures for the production of textiles, what properties are desirable for textiles in garments, and what causes these properties, by breaking down the hierarchical structure level by level.
The final chapter on 3D printed textiles summarizes what has been written about 3D printed textiles in literature, and concludes with a benchmark of 3D printed garments.

The following questions are answered in this part:

- What are the opportunities and limitations provided by additive manufacturing for garment production?
- What properties should a textile have to be suitable for garments?
- How do textiles obtain these properties?
- Why are some textiles more suitable for garments than others?
- How do materials and structures influence textile properties?
- What are 3D printed textiles?
- What has already been done in the field of 3D printed textiles?

PART II: MATERIAL CHARACTERIZATION

In this part, 3D printed textiles as a material are further explored. By means of the findings of the previous section, a classification and definition of 3D printed textiles are proposed. The influence of material, structure and process on the resulting material is discussed in a technical characterization of 3D printed textiles, including a life cycle analysis of two types of 3D printed textiles found in the benchmark to indicate their sustainable impact. Four samples are used for an experiential characterization.

The next chapter shows a number of samples that have been created throughout the project, by means of their technical and experiential characteristics and design options. Finally, the findings

from the (obtained) samples and tests are discussed.

The research questions answered in this part are:

- What are the boundaries of 3D printed textiles?
- What is the environmental impact of 3D printed textiles as compared to traditional textiles?
- What meanings are attributed to 3D printed textiles?
- How do material, structure and process influence the properties of 3D printed textiles?

PART III: MATERIALS EXPERIENCE PATTERNS

This part starts with the creation of a future vision, by means of analysing three fields from the context of 3D printed textiles: additive manufacturing, garments/fashion, and sustainability. Two themes were found relevant for these fields: slow fashion and personalization. These form the basis for a vision statement and metaphor, which explain the qualities for an intended interaction with the material.

From the vision, material qualities have been derived that can be divided in four levels: qualities that are related to the interaction with the material that have been derived from the metaphor; qualities that are related to textile properties; qualities related to 3D printing; and qualities related to sustainability. Finally, the previously created samples are evaluated to determine their fit with these qualities.

The question that is answered in this section:

- What qualities should 3D printed textiles have to optimize an envisioned material experience?

This results in one chosen solution principle to develop further.

PART IV: MATERIAL & PRODUCT DESIGN

In this part, the chosen material is developed further by means of evaluating it to the material qualities. A final material proposal is presented that is thought to fit best to the intended material experience. The unique qualities of this material proposal are evaluated, to find a meaningful product application. Finally, a product design is presented, which is validated by means of a prototype and a life cycle analysis.

This last part answers the question:

- How can the chosen 3D printed textile be applied in a meaningful product design?

PART V: RECOMMENDATIONS AND EVALUATION

The final part gives recommendations for the future production of 3D printed textiles. It concludes with an evaluation of the entire process.

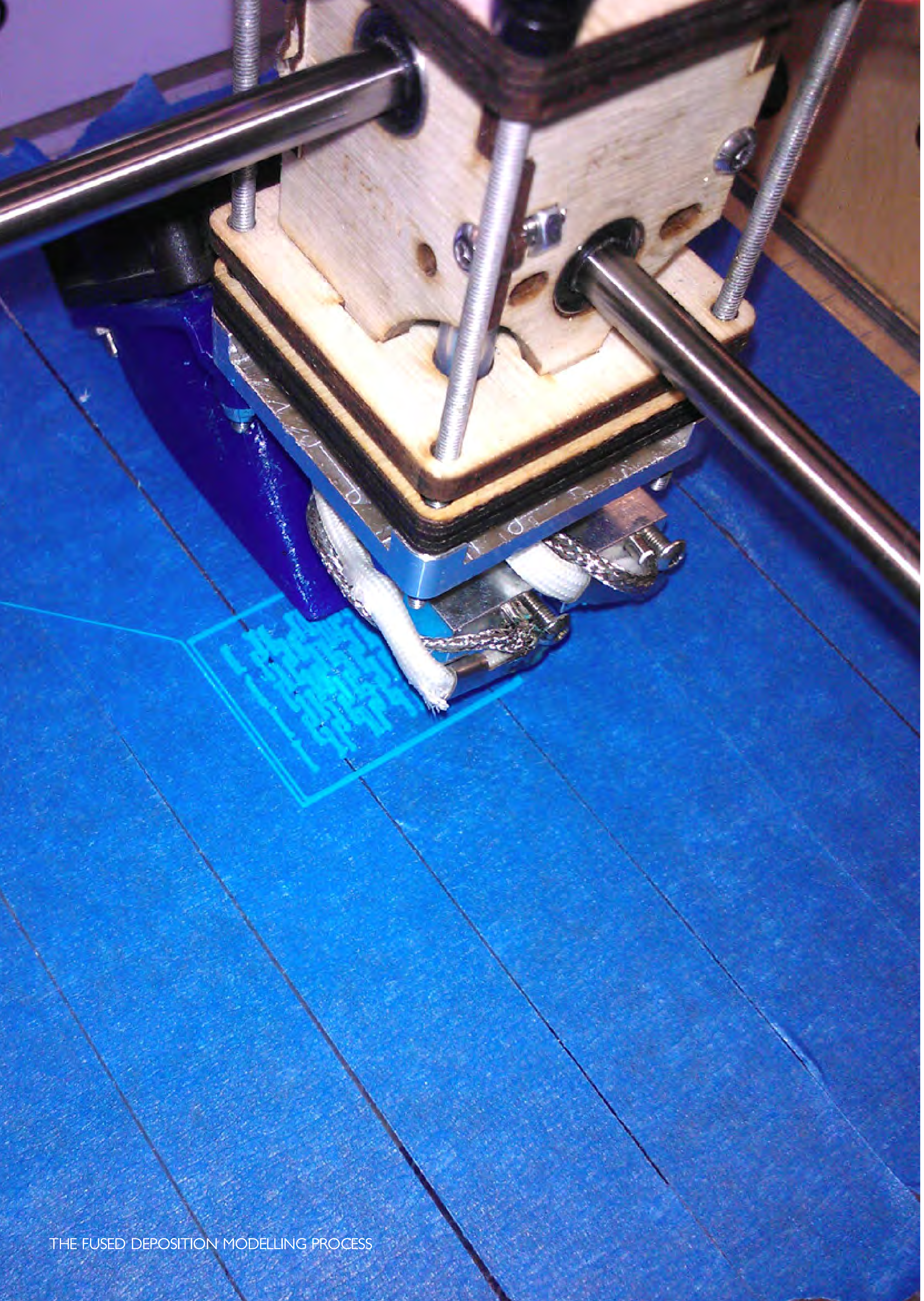
PART I

LITERATURE REVIEW

In this section, the main theoretical framework for the thesis is built. By means of literature research, the subjects of additive manufacturing, textiles and 3D printed textiles have been explored. First, the main concept of additive manufacturing as a technology is discussed, followed by the 3D printing processes that were used during this project. The chapter concludes with a discussion of the factors that can contribute to the production of garments, and those that still need development.

Next to that, the nature of textiles is investigated. This chapter discusses how textiles obtain their flexibility, what factors influence the feeling of a textile and the factors that maintain the structure of a textile, by breaking them down into hierarchical levels.

Finally, in the last chapter the available literature on 3D printed textiles is reviewed. It summarizes what has been written about 3D printed textiles in literature, and concludes with a benchmark of 3D printed garments.



THE FUSED DEPOSITION MODELLING PROCESS

4. ADDITIVE MANUFACTURING

4.1 WHAT IS ADDITIVE MANUFACTURING?

Additive manufacturing (AM), rapid manufacturing or 3D printing is the collective term for all processes that can form a 3D product by means of adding material, rather than by subtracting material. The information for these products comes from a 3-dimensional computer-aided design (CAD) model, which is sliced in discrete layers [Bingham et al., 2007]. These slices correspond directly to the layers that are build by the AM process, allowing the production of virtually any geometry. This process is depicted simplified in Figure 03.

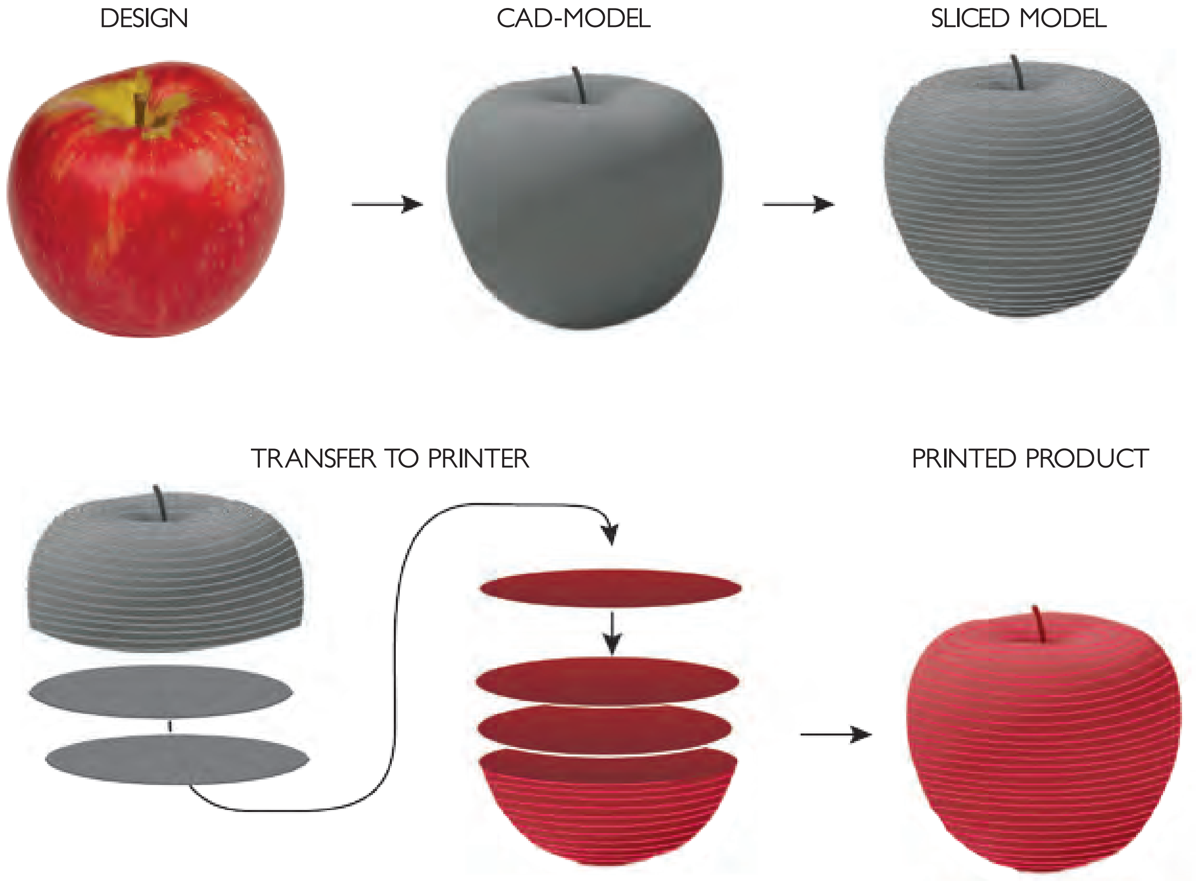


FIGURE 03. 3D PRINTING PROCESS FROM DESIGN TO PRINTER

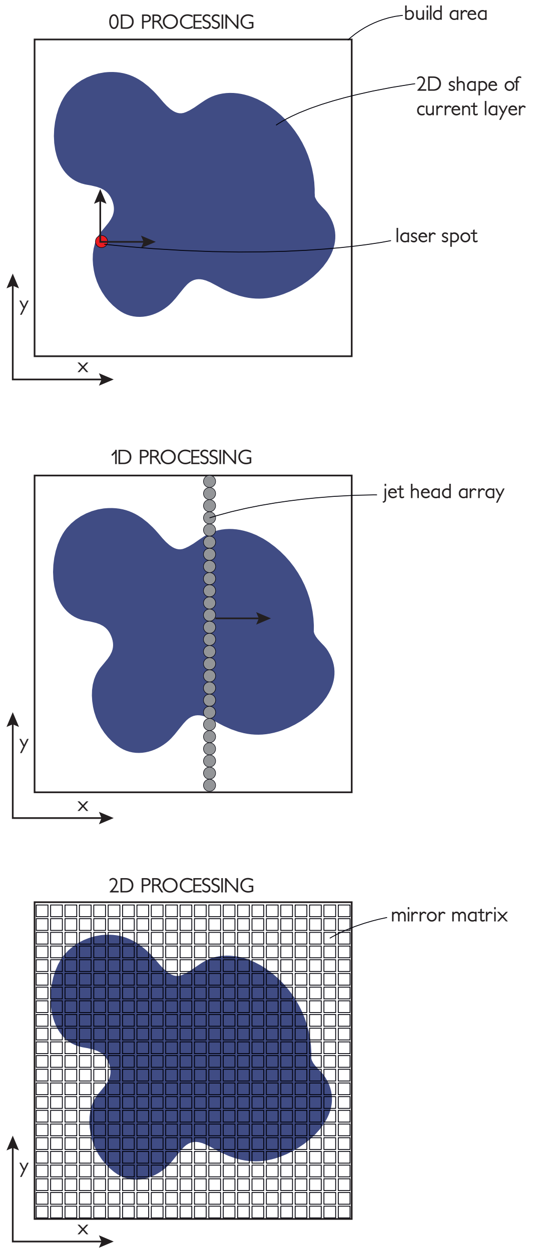


FIGURE 04. 0D, 1D AND 2D PROCESSING (TOP VIEW)

4.1.1 LAYER PROCESSING

The nature of AM processes can be described in terms of layer processing. Material within a layer can be processed sequentially, where the shape of the layer is formed by a single-spot laser. This is termed 0D (although in reality the spot does have a surface area), in which the laser needs to scan in both an X- and Y-direction to cover the entire layer area [Hopkinson and Dickens, 2006], as shown in Figure 04.

Layer processing can also happen simultaneously in arrays or matrices. In case of arrays, this is termed 1D, in which the array is in one dimension (Y) and the printhead only needs to move in one direction (X) to form a complete layer [Hopkinson and Dickens, 2006]. The term 2D is used for matrices, in which a two dimensional matrix covers an entire area, without the need to scan or move [Hopkinson and Dickens, 2006].

Although most AM technologies still use 0D-processing, 1D and 2D processing are gaining territory in order to achieve a higher-throughput and lower costs [Hopkinson and Dickens, 2006].

4.2 COMMON ADDITIVE MANUFACTURING PROCESSES

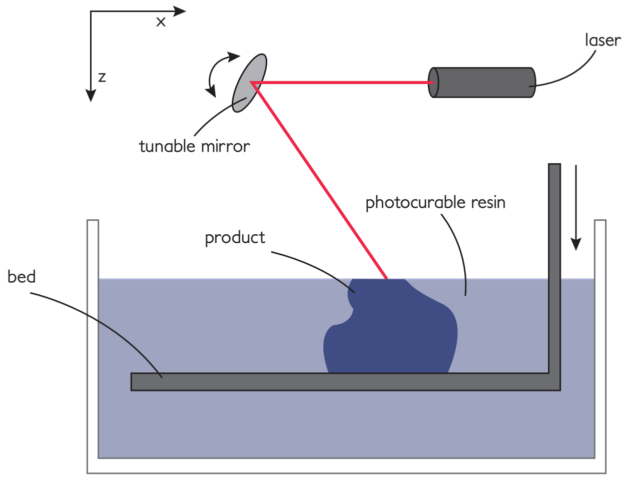


FIGURE 05. STEREOLITHOGRAPHY

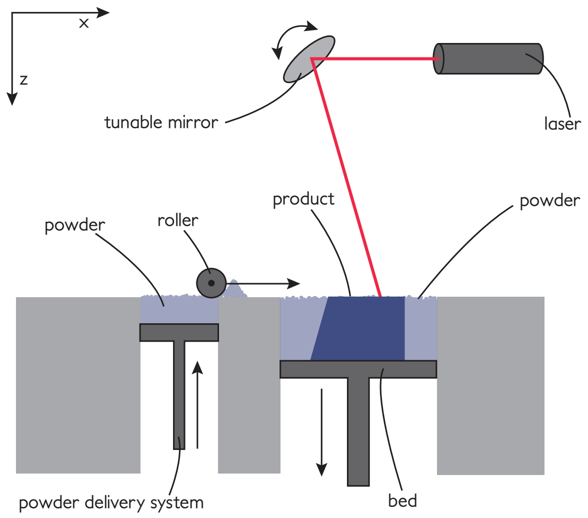


FIGURE 06. SELECTIVE LASER SINTERING

What all AM processes have in common is that they produce a 3D object by means of adding material, rather than subtracting material, as is common in traditional manufacturing processes. The difference between the processes lies in the manner in which material is added. They can be classified by seven standardized terms, used to describe the different nature of the processes [Newman, 2012]:

- Vat Photopolymerization: a process in which a liquid photopolymer is cured layer-by-layer by means of a light/uv-source;
- Material Jetting: in this process, droplets of material are deposited on a build plate in order to construct the layer;
- Binder Jetting: an additive process in which a liquid bonding agent is selectively deposited to join powder materials;
- Material extrusion: in this process, material is dispensed through a nozzle;
- Powder Bed Fusion: thermal energy is used to selectively fuse the regions of powder. Selective Laser Sintering is an example of this process;
- Sheet Lamination: sheets of material are bonded together and cut to the desired (layer) shape in order to build the product.
- Directed Energy Deposition: in this process, materials are melted together by means of focused thermal energy, while they are being deposited.

Appendix A gives an extensive overview of different processes and their characteristics. Four processes that were of particular relevance to this project, because of their accessibility, will be discussed in more detail: Stereolithography (SLA), Selective Laser Sintering (SLS), Fused Deposition Modelling (FDM) and PolyJet technology.

4.3.3 STEREOLITHOGRAPHY

Stereolithography is a vat photopolymerization process. The process is schematically shown in Figure 05. An ultraviolet laser is used to cure a liquid photopolymer layer by layer. The laser is driven by a CAD-file, which cures a selected part of the polymer on to a platform. The platform is lowered in tiny steps (typically around 100 μm), allowing a new layer of liquid polymer to flow over the previous layer, which can then be cured by the laser [Hopkinson and Dickens, 2006]. SLA is an example of a 0D-processing.

The main advantages of SLA are its high accuracy and good surface finish, resembling injection moulded parts [3D Systems, Inc., 2014]. However, material properties of this process are poor, especially over time. The materials are often sensitive to humidity, and exposure to sunlight can cause the material to continue curing, which affects the mechanical properties and appearance [Hopkinson and Dickens, 2006].

4.3.4 SELECTIVE LASER SINTERING

This powder-based process is similar to SLA, although instead of a liquid polymer a powdered material is used. As shown in Figure 06, a laser sinters the powder on top of the powder bed, after which a new layer of powder is added by rollers to the top. In this way, the laser builds the product out of two-dimensional layers by means of 0D-processing. The powder that is not fused by the laser acts as a support material, which can be removed using compressed air, and afterwards partly reused. In order to reduce thermal gradients and reduce the energy required for the laser, the powder is preheated to a temperature a few degrees below the melting temperature [Hopkinson and Dickens, 2006]. However, this also partially degrades the powder, which is why approximately 10-40% of the powder ends up as waste [Telenko, 2010].

Advantages of SLS are more stable parts, good mechanical properties and a large variety of materials that can be used. A disadvantage is the poor surface quality, which requires extensive finishing processes for some parts, if a smooth surface is desired.

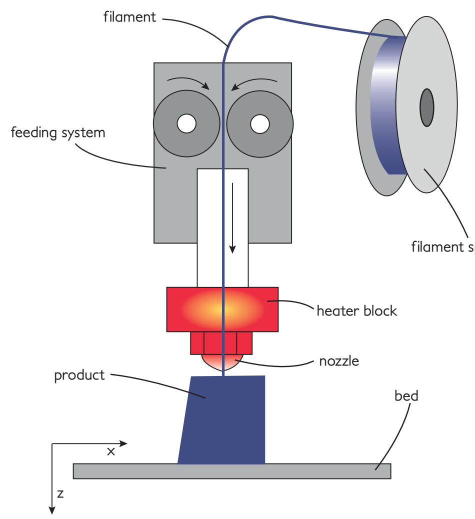


FIGURE 07. FUSED DEPOSITION MODELLING

4.3.5 FUSED DEPOSITION MODELLING

The term Fused Deposition Modelling was first commercialised and patented by Stratasys. In response, other companies adopted the term Fused Filament Fabrication (FFF), in order to be used legally unconstrained [RepRap, 2014]. Both terms refer to the same solid-based process, in which the material is extruded through a nozzle, as shown in Figure 07. The nozzle extrudes and deposits material layer by layer. The resolution of the part is limited by the diameter of the nozzle (typically around 0,3 mm) [Hopkinson and Dickens, 2006]. Due to the nature of the process, creating overhanging parts is limited without the use of a support structure, which later has to be removed. The process is easy to set-up and has become the most popular choice for home-use.

4.3.6 POLYJET TECHNOLOGY

In PolyJet technology, an array of printing heads is used that simultaneously deposit material (1D processing), as depicted in Figure 08. The material is an acrylate-based photopolymer, which is hardened using a UV-lamp [Hopkinson and Dickens, 2006]. The accuracy of the layers can be up to 16 μm [Hopkinson and Dickens, 2006]. During the process, support material is added automatically, which can later be removed using a water jet. The latest innovation in PolyJet technology is the ability to print using multiple materials at once, for instance a hard material can be mixed with a flexible material in the same part.

Besides the possibility of printing multiple materials, PolyJet technology offers a high resolution, the ability to print complex parts and no need for additional post-processing, except for removal of the support material. However, PolyJet technology requires expensive equipment and is not (yet) suitable for home use.

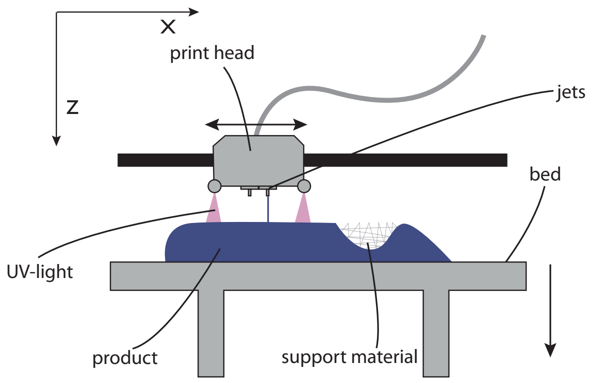


FIGURE 08. POLYJET TECHNOLOGY

4.3 OPPORTUNITIES AND STATE-OF-THE-ART

This section discusses the opportunities provided by additive manufacturing for the production of garments, followed by an overview of the state-of-the-art of the technology and future developments. All factors are summarized in Table 01.

OPPORTUNITIES	
SHAPE COMPLEXITY	design optimisation
	part consolidation
	customization
	multiple assemblies
	reduction in process steps
MATERIAL COMPLEXITY	heterogeneous materials
	property gradients
HIERARCHICAL COMPLEXITY	microstructure
	macrostructure
	mesostructure
FUNCTIONAL COMPLEXITY	functional devices
	pre-assemblied parts
STATE-OF-THE-ART BOUNDARIES	
PROCESS LIMITATIONS	CAD systems
	support structures
	process time
PRODUCT LIMITATIONS	available materials
	size
	resolution
HUMAN LIMITATIONS	2D thinking

TABLE 01. OPPORTUNITIES AND CHALLENGES OF AM FOR TEXTILES

4.3.1 OPPORTUNITIES FOR GARMENT PRODUCTION

The opportunities provided by additive manufacturing related to garment design can be divided into shape complexity, material complexity, hierarchical complexity and functional complexity.

Shape complexity

One of the major benefits of additive manufacturing is the possibility to make almost any geometry, without extra costs. This provides opportunities to optimise complex designs for their intended functions, for instance by combining many components into one. This approach allows designing specifically for the intended function, without adding unnecessary weight or parts [Hague, 2006]. A reduction of assemblies is beneficial not only for cost reasons, but also because no compromises have to be done for manufacturing and assembly reasons [Hague, 2006]. In garment design, closures could for instance be included during production, as has already been done by Freedom of Creation (Figure 10).

Another benefit of shape complexity is the reduction in process steps. The entire product development process is sped up by the use of computers throughout the process [Gibson, Rosen and Stucker, 2010]. The production process itself is generally performed in a single step in additive manufacturing, although in most cases finishing processes are required.

Body fitting customization is another opportunity provided by additive manufacturing. Traditionally, customized products are very labour intensive, since the machine settings have to be adjusted for every new product. However, additive manufacturing can make this process more economically viable, by allowing the process characteristics to essentially stay the same [Hague, 2006]. Especially combined with 3D scanning, customized products could be within reach for a larger public, which means standardized sizing could become obsolete.

Finally, complexity in shape allows the creation of multiple assemblies in one production process. This is more thoroughly discussed in chapter 9.1.1

Material complexity

Traditional manufacturing techniques are often only able to form one homogeneous material at a time. This limits the functionality to the properties of one material only. Additive manufacturing has given rise to the opportunity to deposit multiple materials in any location or combination necessary, which is termed *functionally graded materials* (FGM) [Hague, 2006]. Although this is not yet

FIGURE 10. WEEKEND BAG WITH INTEGRATED CLOSURES, BY FREEDOM OF CREATION

FIGURE 09. COLLAPSING A 3D STRUCTURE [BINGHAM ET AL, 2007]

fully optimised, it is becoming a more viable concept by development of multi-material 3D printers.

Not only the use of heterogeneous materials, but also the possibility to create different material properties by means of structure is an opportunity. The nature of many AM processes enables changing the material composition in gradients or abruptly [Gibson, Rosen and Stucker, 2010].

Material gradients could be used in the production of garments to optimise certain parts for their function; for instance the bottom of a bag could be printed in a hard, rigid material (providing the necessary stiffness), while the sides are made of a soft and flexible material.

Hierarchical complexity
Hierarchical complexity includes the micro-, meso- and macrostructure of a part. Additive manufacturing allows for all these structures to be controlled and designed in order to obtain desired properties. The idea behind this is that every feature can have a smaller feature added to it, and all of these smaller features can also have smaller features added to them etc. [Gibson, Rosen and Stucker, 2010] This can be expressed in three examples: tailored microstructures, textured surfaces and cellular materials (materials that are designed to have material only where it is needed, which results in light, stiff and strong materials [Gibson, Rosen and Stucker, 2010]).

The microstructure of the material can be controlled by adjusting various parameters of the additive manufacturing process. Geometries larger than 0,1 mm are referred to as mesostructures, and are typically associated with truss-like structures [Rosen, 2007].

Functional complexity
Due to the nature of the additive manufacturing process, it is always possible to have access to the inside of the part. This makes it possible to fabricate operational mechanisms during the process, or to insert prefabricated assemblies [Gibson, Rosen and Stucker, 2010]. This provides opportunities especially for smart textiles and wearables.

4.3.2 STATE-OF-THE-ART

As discussed above, there are many opportunities of 3D printing that would benefit garment production. However, the production of garments and textiles by means of additive manufacturing has not yet been broadly applied. There are a number of practical reasons that limit the implementation of this technology, which are related to the current state-of-the-art of the technology. These factors are discussed in the following section.

CAD modelling systems
Although the additive manufacturing process allows parts to be made up of many small elements, most commercial CAD systems cannot perform calculations with more than 1000-2000 elements [Gibson, Rosen and Stucker, 2010]. Modelling complex 3D structures is therefore difficult and time-consuming. Another challenge is modelling a textile-like structure that is curved, for instance in the shape of a human body. Moreover, when designing a product made of AM textile, it must be produced in its final shape. Since the number of layers or *z-height* is responsible for the largest portion of the costs [Hague, 2006], the most efficient manner to do this is by 'collapsing' the product under its own weight, as shown in Figure 09 [Bingham et al., 2007]. Current CAD systems are not designed to execute these types of calculations. Therefore, the potential of additive manufacturing for multiple assemblies is restricted by the developments in CAD systems.

Need for support structures
Depending on the geometry and process, it might be necessary to include support structures in the model. Supports are required in parts with overhanging structures or in multiple assemblies, since these consist of separate links. In the material extrusion process, it is possible to print supports of a different, water-soluble material, however more often the supports need to be removed by hand. For complex geometries, this is a tedious and time-consuming process, and there is a risk that the part gets damaged. Especially for parts made with multiple assemblies, such as AM textiles—in which there are many small links, removing the support by hand is almost impossible. In that case, soluble materials can be a solution, although since these are flushed away they are not the most environmentally friendly option. In any case, the use of large quantities of support material almost diminishes the advantage of the low-waste process.

Process time
A 3D printer can take hours to build a large, complex product. The specific time depends on the type of process, the height and build-density of the part and the volume of the support [Telenko, 2010]. However, this can be put in perspective by the fact that additive manufacturing reduces the total process time by minimizing the number of steps (as discussed above). Still, 3D printing has the reputation of being a very quick process, which can be misleading to some people when confronted with the actual build times.

Size limitations
The size of the product that can be produced is dependent on the size that is available in the 3D printer. If the part is too large to fit in the printer, it can be cut into several smaller parts and assembled later. Although most printers are still limited in size, developments are ongoing; for instance DUS Architects are in the process of 3D printing a canal house in Amsterdam [Coevert, 2014]. However, currently the size of the part is restrained by the size of the printer.

Material limitations
The number of materials that can be 3D printed is still limited. For most processes, there are a number of plastics available, as well as metals and ceramics. Other types of materials are in development, but currently most research focuses on materials that can be melted in order to be used in the current printing processes. In order to be able to also print different materials, different printing technologies will need to be developed for their specific properties.

Limited resolution
The key to creating printed materials that have similar properties as textiles, is mimicking their small structure. In order to create these small structures, the printing resolution needs to be increased.

2D Thinking
Although in theory it is possible to create entire 3D garments in one process, there is a knowledge gap that prevents it from being frequently used in practice. Fashion designers are commonly the people that design clothing, however they are not trained to work with 3D modelling programs. Their education focuses on thinking in 2D patterns, rather than 3D products. Therefore, it is suggested by some to first get fashion designers acquainted with additive manufacturing by printing 2D pattern pieces [J. Mikkonen 2014, pers. comm., 7 April], since these can be created relatively easily with limited modelling skills, and fashion designers know how to work with these. In the long term, it would be beneficial if the entire process of 3D-modelling could be simplified, or more optimised for the specific requirements for garment design.

4.3.7 THE IMAGE OF 3D PRINTING

Additive manufacturing is one of the most upcoming technological advancements of the moment. As a result, it receives a formidable amount of attention in the media. These developments are often described as the age of digital technology, of which additive manufacturing is only the beginning. Some media even predict a third industrial revolution [The Economist, 2012]. Because of these high expectations, the tone with which is spoken about 3D printing is one of excitement, anticipation and innovation. This is directly visible in the image people have of 3D printing: unlimited possibilities, and the creation of new, amazing products that could previously not be created. This functional image is often combined with customization; this is especially visible in the numerous reports of printed prosthetics.

Sustainability is also a value attributed to 3D printing, although often not well substantiated. It is attributed to the reduction of waste material as a result of the additive process and the reduced number of production steps.

Although this positive image of the additive manufacturing process will most likely contribute to the acceptance of 3D printed garments, it also means that if the product itself is perceived as not exciting or plain, it will clash with the expectations of the user, which may result in a negative attitude towards the product.

4.4 CONCLUSIONS

As shown in this chapter, 3D printing provides a lot of benefits for the production of garments. 3D printing makes it possible to create personalized garments, in virtually any shape, and reduces the number of production steps. It also allows localized differences in material and structure, optimized for changes in functionality within one product.

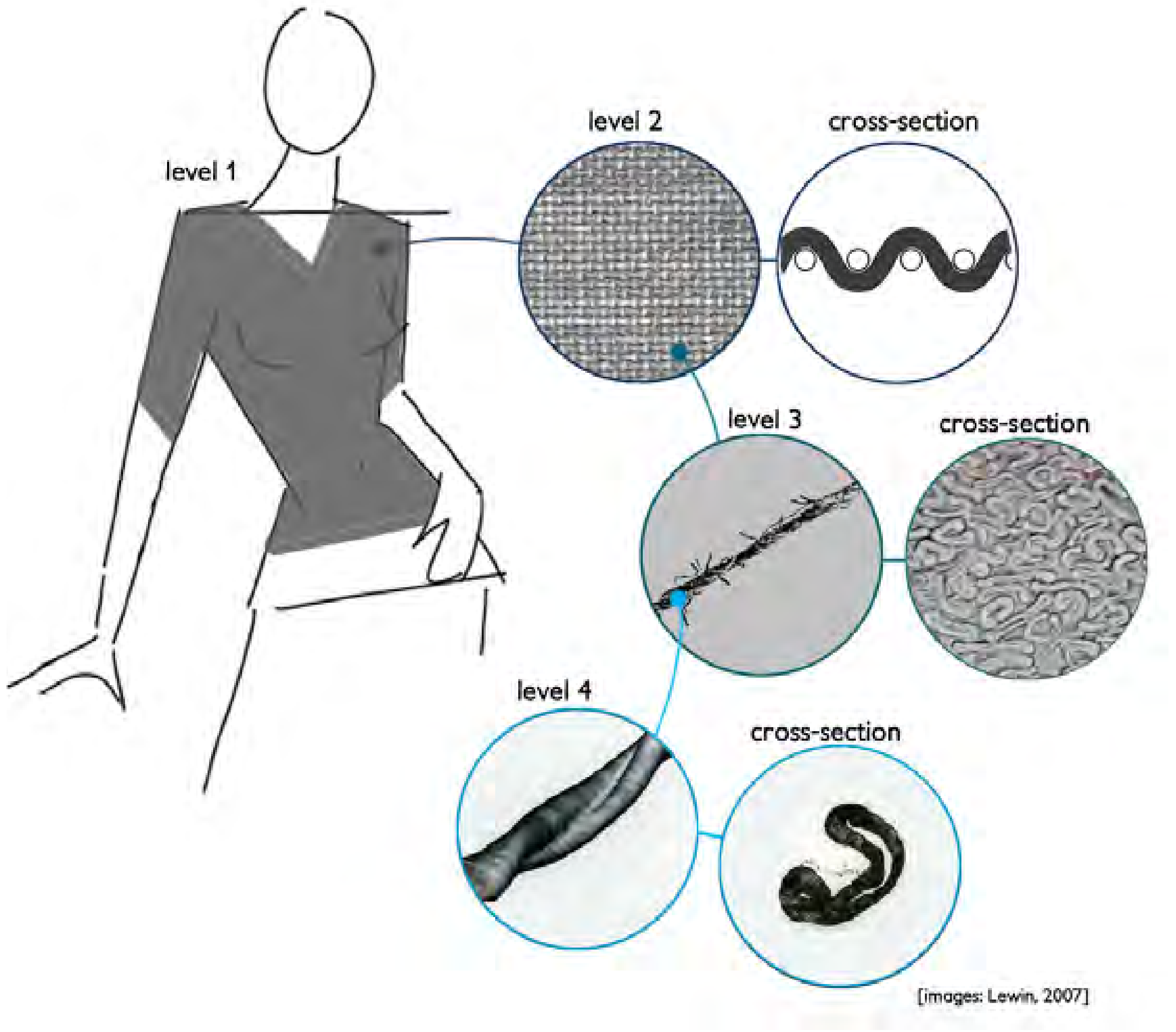
On the other hand, the technology still needs to develop further before this can become reality. Advances in CAD systems, in printing technology and, most importantly, in the way we think of and design garments are necessary in order to 3D print functional garments: we still tend to think about products by the limitations imposed by Design for Manufacturing and Assembly, instead of thinking in a way allowed by the possibilities of 3D printing.

This chapter has also shown that there are a number of different printing processes. There is no ideal process; the choice of process should depend on the desired design and properties.

Therefore, since the production of garments by means of AM still has a long way to go, it is necessary to first determine in what ways the opportunities of AM could be of most value, as has been done in this chapter, in order to create truly meaningful products.

5. GARMENTS AND TEXTILES

5.1 THE STRUCTURE OF GARMENTS



[images: Lewin, 2007]

FIGURE 11. HIERARCHICAL STRUCTURE OF GARMENTS

In order to design a meaningful product using 3D printed textiles, it is useful to look at the properties that should exist in the finished product. The situation for garments is that they are in essence all constructed from a sheet material into a 3D product. In the next section, the hierarchical structure of traditional garments is discussed, on four levels.

5.1.1 DEFINITION OF TEXTILE

The definition of a textile is "any filament, fiber, or yarn that can be made into fabric or cloth, and the resulting material itself" [Encyclopaedia Brittanica, 2014]. It includes woven, knitted and non-woven fabrics, but also threads, ropes, lace and nets. Essentially, traditional textiles are flexible materials that consist of interlaced fibers. Textiles in garments are used as an interface between our bodies and the environment, in which they function as a barrier, for instance for temperature or water [Carpi et al., 2007]. However, nowadays garments have gotten many more symbolic functions, for instance self-expression, identification, status and belonging to a group [Fletcher, 2000].

5.1.2 HIERARCHICAL STRUCTURE

When examining garments more closely, it becomes apparent that they can be thought of as existing of multiple levels. For each level, it is possible to distinguish a structure that is characteristic for that level.
Figure 11 shows a schematic of the hierarchical structure of clothing made out of a woven textile. The level of hierarchy ranges from 1 to 4, with level 1 representing the top component - the garment - and level 4 representing the smallest component: the fiber. Fibers are used to create yarn, after which the yarn is knitted or woven into flat sheets of textile. The flat sheets are then created into a garment, by means of cutting out pattern parts and attaching them to each other by techniques as described below.

5.1.3 STRUCTURES AND TECHNIQUES

The structures applied in garments are important in order to create a well-fitting piece of clothing. Structures for shape (besides the actual shape of the pattern pieces) include darts and multiple layer structures. Permanent fastening techniques include sewing and gluing, although sewing is the most widely used. The seams created by sewing can either be functional or decorative. If the garment is not elastic, non-permanent fasteners (closures) need to be included in the garment in order to put it on, such as zippers and buttons.

5.2 TEXTILE PRODUCTION

It is possible to distinguish three types of structures for textiles: woven, knitted and non-wovens. Their characteristics are discussed in the next sections.

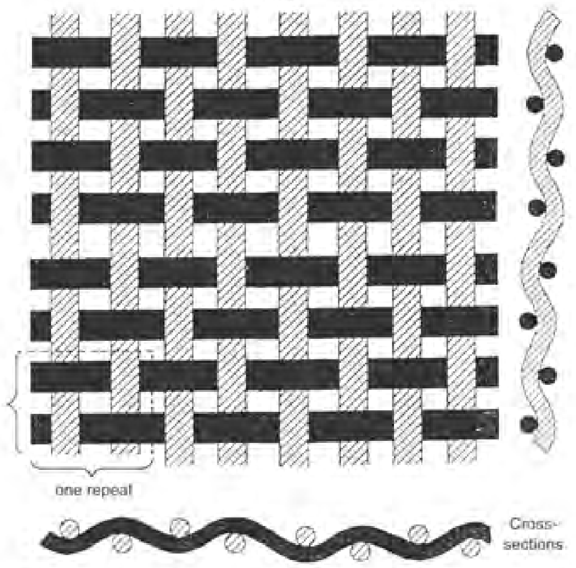


FIGURE 12. A PLAIN WOVEN FABRIC [SONDHELM, 2000]

5.2.1 WEAVING

Weaving is the process in which two sets of threads are interlaced to create a flat structure. The two sets of threads are called warp and weft, in which the warp represents the length of the fabric and weft the width of the fabric. This is shown in Figure 12. Due to the friction between the separate threads of yarn, the structure of the fabric remains intact. In theory, an unlimited number of weave structures can be developed, although most are derived from the plain weave shown in Figure 12. The characteristics of woven fabrics, such as strength, stiffness, stability and porosity are determined by several factors, including the type of fiber (natural or man-made), the type of yarn (thickness; mono/multi-filament; flat/textured; twist factor) and the density of weaving. Generally speaking, woven textiles are stronger and more stable than other textile structures [Sondhelm, 2000]. They have low elasticity, but are easier to cut and sew than knitted structures.

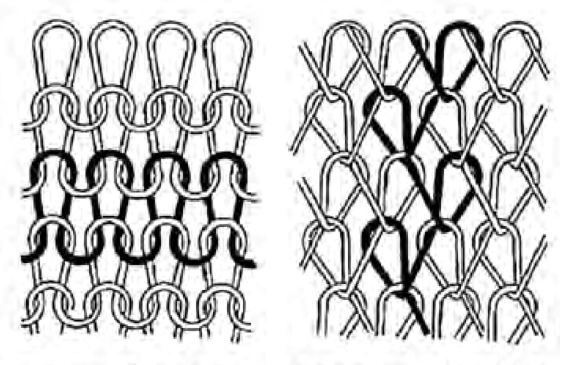


FIGURE 13. A WEFT-KNITTED FABRIC (LEFT) AND A WARP-KNITTED FABRIC (RIGHT) [CAPRI ET AL., 2007]

5.2.2 KNITTING

The term knitting is used to refer to the construction of a fabric consisting of interconnected loops of yarn. Because of this structure, the resulting fabric is elastic and porous, able to provide warmth (due to the entrapment of air) and has soft draping qualities. Knitted fabrics tend to resist wrinkling and are light-weight.

Warp and weft knitting are two of the most common knitting methods, as depicted in Figure 13. The difference between the two is direction in which the thread is fed. In a warp knitted fabric, the warp thread is fed into the direction of the fabric (longitudinal), in a weft knitted fabric the thread is fed at a right angle to the direction of the fabric (transversally) [Carpi et al, 2007].

There are many different knitting machines, suitable for different types of knits. One common ground is that the knitting thread always has to be fed above and below the other threads, called overlap and underlap respectively. The structure can be as complicated as necessary, depending on the desired properties.

Knitted structures are subject to relaxation, which permanently alters their geometry. Dry relaxation occurs right after production, and is caused by the fact that the tension applied during production is lifted from the yarns. Further relaxation during production can be achieved by soaking the textile in water and heating it. During use, relaxation occurs over time due to wear, washing or improper use.

The characteristics of knitted fabrics are determined by the following factors:

- The structure of the knit: it was found by Emirhanova and Kavusturan (2008) that the knit structure has a significant effect on strength, porosity, bending rigidity (drape) and abrasion resistance. The knit structure also determines the aesthetic properties, the elasticity and the warmth of the fabric;
- The type of fiber;
- The stitch length;
- The yarn linear density, which determines the tightness of the fabric and inherently the drape.

5.2.3 NON-WOVENS

The group of non-woven textiles contains all fabrics that are produced by processes other than knitting or weaving. Commonly, non-wovens exist of webs of interlocking fibers, that are bonded by mechanical, chemical or thermal means [Smith, 2000; Patel, n.d.].

The main difference between non-wovens and knitted or woven fabrics, is the fact that the latter two are made out of yarn. Since yarn is not used for non-wovens, their production process is quicker and simpler [Duqesne, 2007].

A very wide range of properties can be obtained by non-woven textiles, all depending on the production process – which determines how the fibers are arranged, the type of fiber and the type of bonding used [Patel, n.d.]. Smaller fibers are preferred for a number of reasons: they have a better filament distribution, which means the pores are smaller causing better filtration, a softer feel and lighter fabrics [Smith, 2000].

The common factor for all non-woven production processes is that they are performed in two stages: the first stage is preparation of the fibers, the second stage is the bonding process. There are a lot of different processes for fiber preparation, as well as bonding processes. Most of these processes can be combined with each other, which means there are even more different manufacturing lines possible.

During fiber preparation, the fibers are arranged in a so-called web, which is a thin layer of fibers. Consequently, a batt is formed by stacking a number of webs on top of each other. The production process from raw materials to bonding is often continuous [Smith, 2000].

The properties of non-wovens are dependent on a large number of factors, including the type of fiber, the bonding agent, and the orientation of the fibers.

Fiber orientation

The orientation of the webs of fibers depends on the production method. There are three possible configurations:

- Parallel laying: in which the fibers are placed in the machine direction (which is the length of the fabric);
- Cross laying: in which the fibers are oriented perpendicular to the machine direction (across the width of the fabric);
- Random laying: in which the fibers are oriented randomly.

Since the fiber strength is always higher than the strength of the bonding agent, the direction in which the fibers are oriented will be the strongest direction [Smith, 2000].

Bonding methods

The web of fibers can be bonded together by mechanical, chemical or thermal means [Patel, n.d.].

In mechanical bonding, the fibers are entangled together. This can be achieved by using needles to hook fibers or by using high-pressure water jets [Duqusene, 2007].

In chemical bonding, a bonding agent is used. The choice of bonding agent is important, since it partly determines the characteristics of the fabric. Common bonding agents are butadiene copolymers, acrylates and vinyl copolymers. They can be used in liquid, foam or powder form, depending on the used process. The use of different bonding agents will result in different textile properties.

Thermal bonding uses heat as a main method for bonding, and is based on the ability of some fibers to fuse when exposed to heat [Duquesne, 2007]. It is often used in addition to other bonding processes.

In some processes, such as melt blowing, the fibers are not bonded together at all, but simply stick together. In melt blowing a polymer is used, which is blown into ultrafine fibers by means of hot air, after which the fibers are sprayed onto a surface and cooled by cold air. The fibers need to be as fine as possible, in order to achieve more fiber-to-fiber contacts to keep the batt intact [Smith, 2000].

5.3 YARN

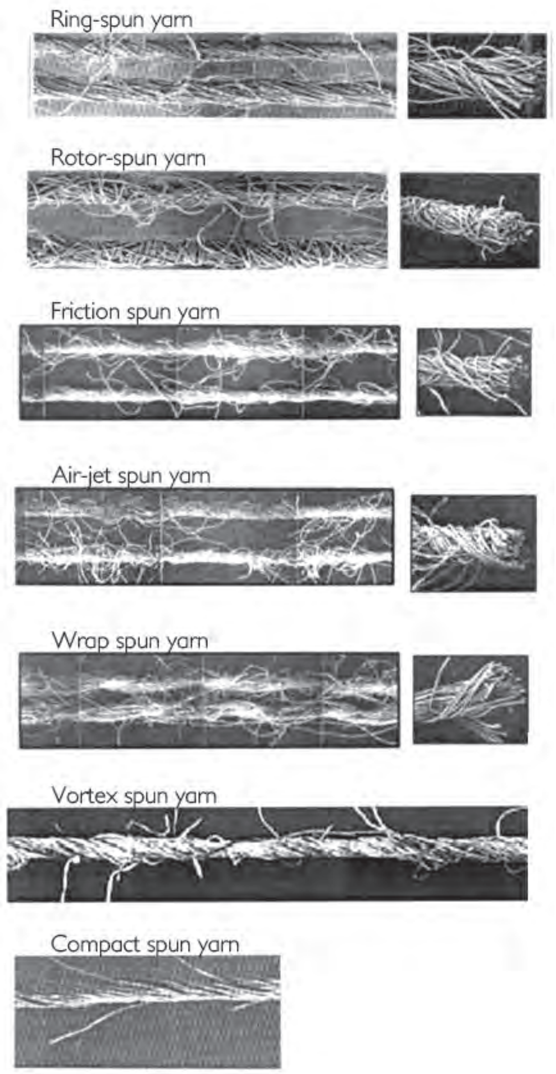


FIGURE 14. YARN STRUCTURES FROM DIFFERENT SPINNING PROCESSES [GOSWAMI, 2004]

A yarn is a strand composed of fibers or filaments, which is created by means of spinning. The spinning process consists of three consecutive steps. The first step is drafting of the fibers, in which the fibers from the input strand are aligned along the axis of the yarn in the appropriate density. A typical yarn will contain approximately 100 fibers in the cross-section [Lewin, 2007]. The second step is binding the fibers together, by providing enough cohesion so they form a uniform thread. This can be accomplished by twisting, entangling, wrapping or bonding the fibers. The last step is wrapping the yarn around a bobbin or some other type of packaging.

There are several spinning systems that perform these three steps in different ways, which will not be discussed in detail here. Figure 14 shows the yarn structures obtained by different spinning processes. The type of spinning process chosen depends on the characteristics of the input fibers and the desired properties of the yarn.

As can be seen in Figure 14, the yarn produced by all spinning methods contains certain 'hairiness'. This yarn hairiness is caused by loose fiber ends, 'looped' fibers or wild fibers that stick to the yarn [Goswami, 2004]. The hairiness of a yarn does not depend on the level of twisting, but is generally caused by uneven length of fibers in the staple [Goswami, 2004]. When more fibers are protruding from the yarn body, the yarn will be weaker and fabric made from these yarns has a rougher feel and a 'hazy' appearance.

The thickness of the yarn is of large influence to the properties of the final fabric. Thicker yarns will result in a thicker, more robust fabric, while thinner yarns will create a better drape and a softer material.

5.4 FIBERS

Fibers are long, thin and flexible materials. They have a large length to thickness ratio, usually in the order of a 1000 or higher [Goswami, 2004]. This is defined as the slenderness ratio, which is responsible for the inherent flexibility, fineness and softness of fiber materials.

Fibers for textiles can be divided into two categories: natural and man-made. Natural fibers can be divided into vegetal, animal and mineral fibers. Their main components are either cellulose or protein [Duquesne, 2007]. Man-made fibers can be synthetic or regenerated; for the latter it means that the fibers are regenerated from natural sources [Goswami, 2004]. Table 02 shows an overview of the classification of fibers, of which some are discussed more thoroughly in the next section. An extensive overview of the most common fibers and their technical properties can be found in appendix C.

5.4.1 NATURAL FIBERS

Natural fibers account for approximately 45% of the total fiber production [Goswami, 2004]. These fibers have natural attributes that make them desirable for clothing applications. They are often preferred over synthetic fibers, either for status, comfort, or durability reasons, although the latter perception is not entirely funded.

NATURAL FIBERS		
	VEGETAL	cotton wood flax hemp jute
	ANIMAL	silk/spider wool hair
	MINERAL	asbestos
MAN-MADE FIBERS		
	REGENERATED	viscose cupro acetate lyocell casein alginate natural rubber
	SYNTHETIC	acrylic polyester cellulose ester polyurethanes polyvinyl hydrocarbons synthetic rubber polysulfide miscellaneous

TABLE 02. CLASSIFICATION OF FIBERS

All natural fibers are staple fibers (fibers of finite length), except for silk, which is continuous. Short and long staple fibers exist, for example cotton is a short staple fiber (12.5-38 mm), while wool is a long staple fiber (50 -175 mm) [Goswami, 2004].

The three types of natural fibers are discussed more in-depth below.

Vegetal fibers
The main component of all vegetal fibers is cellulose [Duquesne, 2007]. Cellulose is one of the main building blocks of all natural materials, and is an abundant, renewable material. It exists in the form of fibers in wood, cotton and other plants and is the most common organic polymer [Klemm et al., 2005]. Cotton consists of more than 90% cellulose, while the cellulose content of wood is around 40-50%.

The shape and structure of cellulose fibers are responsible for the properties that make it desirable for textiles. This becomes clear when taking a look at cotton fibers. Cotton fibers grow as thin-walled, hollow tubes of cellulose inside the cotton boll. They develop an internal structure as a result of the deposition of thin cellulose layers on top of each other [Goswami, 2004]. These "growth rings" are alternatingly solid and porous. Once the cotton boll opens, the fibers lose their moisture and obtain a kidney-shaped cross section [Goswami, 2004]. In longitudinal direction, the fibers are not straight but slightly twisted. Figure 15 shows the longitudinal and cross-sectional view of cotton fibers [Goswami, 2004].

This structure of the cotton fiber contributes to the desirability of cotton for clothing. The longitudinal twist and surface texture allow the fibers to be twisted and adhere to each other. The alternating layers of fibers in the cellulose and its cross section allow cotton to have good warmth-retention and absorbent properties.

Animal fibers
The source for these fibers is either animal hair or silk. The main component of animal fibers is protein [Duqesne, 2007].
Wool is the most important and widely used animal fiber, of which the main component is keratin, a complex protein [Tridico, 2009]. Its structure and cross-section are shown in Figure 16. It has a circular cross-section, and is shaped like a cylinder with a tapered tip [Goswami, 2004]. This shape causes its natural waviness, in the form of a spiral. The outer layer of the fiber is a water-repellent membrane in the form of scales, with tiny microscopic pores through which water vapour can be absorbed [Goswami, 2004].

The shape of the wool fiber is responsible for its popularity in textile applications. The natural waviness holds the fibers coherently together when twisted, but at the same time causes air to be trapped in the yarn, which forms an insulating layer [Goswami, 2004]. Its spiral structure is also responsible for the elasticity of wool fibers.

Silk is the only continuous natural fiber. Its main component is fibroin, a protein, which forms the structural part of the silk [Tridico, 2009].

Fibroin molecules form hardly any cross-sections or side chains, which allows the fibroin molecules to align themselves parallel to each other and form hydrogen bonds [Tridico, 2009]. Figure 17 shows the fibroin fibers of raw silk before and after extraction.

When a silkworm spins a cocoon, it produces a thin layer of sericin on the surface of the fibroin filament. Sericin is a natural gum: a sticky protective material that hardens when exposed to air, holding the filaments together [Tridico, 2009]. In order to harvest silk, the cocoons are soaked in hot water to soften the sericin and unwind the silk. The layer of sericin is often transferred onto the filament during further processing, in order to prevent damage, although it causes a rougher feel of the silk [Goswami, 2004].

Mineral fibers

The only naturally occurring mineral fibers are asbestos, a collective term for a group of six different mineral fibers. Although they have many desirable properties, such as fire resistance, flexibility and high tensile strength, their renowned health risks have caused a rapid decline in usage.

5.4.2 MAN-MADE FIBERS

Although man-made fibers often aim to copy the properties of their natural counterparts, they can also offer a variety of properties that are not available in natural fibers. Man-made fibers are generally continuous fibers, although they are often subjected to a number of processes to transform them into staple fibers. In theory, man-made fibers can be produced with any cross-section. There are two types of man-made fibers: synthetic and regenerated fibers.

Regenerated fibers

In the production of regenerated fibers, the polymers are derived from natural sources. Common materials that are often regenerated are cellulose (from cotton linters or wood), protein (from milk), zein (from maize) and alginic acid (from seaweed) [Goswami, 2004]. The process usually involves dissolving the polymer in a chemical solvent and forcing it through a spinneret in order to form filament.

Regeneration of cellulose fibers accounts for the largest portion of man-made fibers [Goswami, 2004], since there is a large abundance of cellulose sources, it is inexpensive and it is one of the preferred fibers for textile production.

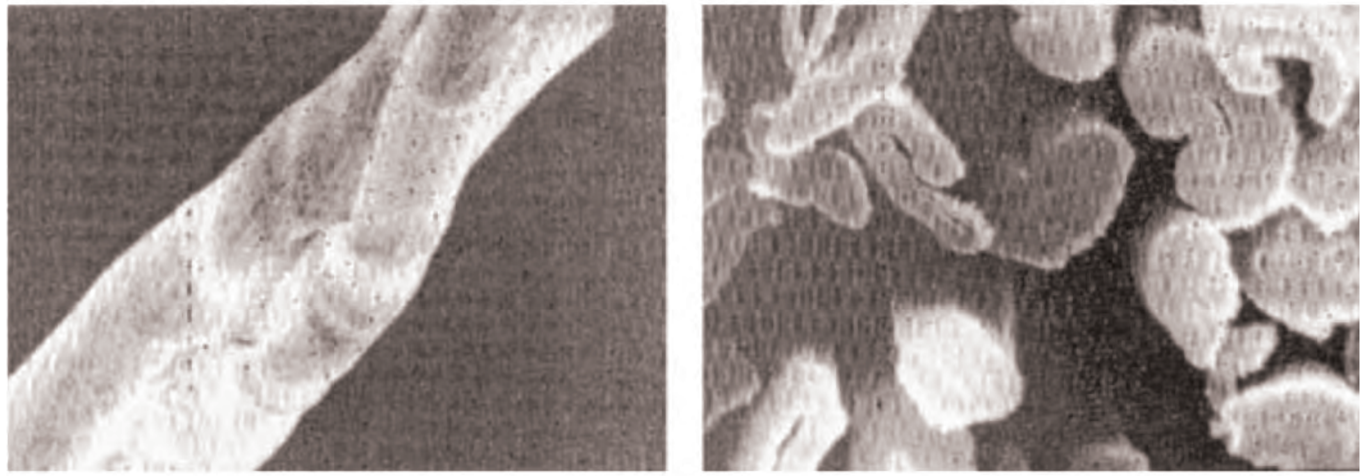


FIGURE 15. LONGITUDINAL (LEFT) AND CROSS-SECTIONAL VIEW OF COTTON FIBERS [GOSWAMI, 2004]

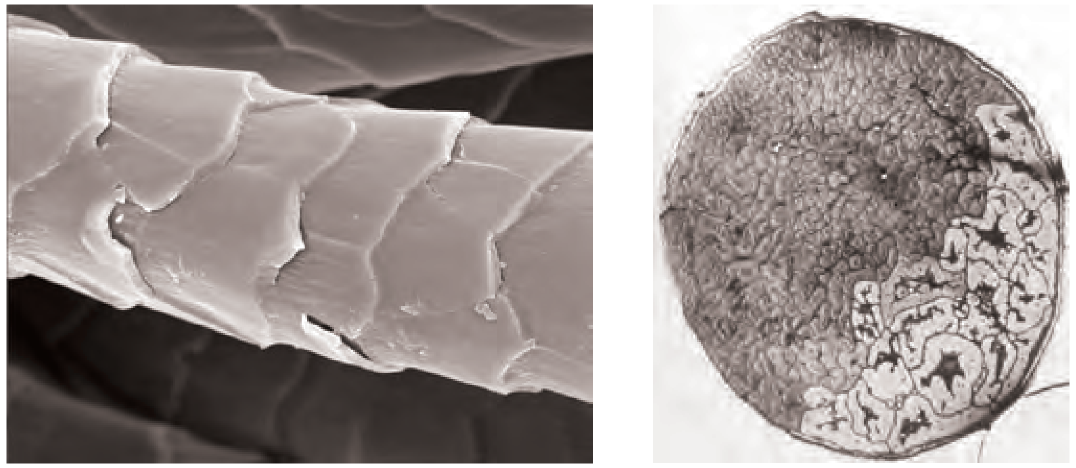


FIGURE 16. LONGITUDINAL (LEFT) AND CROSS-SECTIONAL VIEW OF WOOL FIBERS [GOSWAMI, 2004]

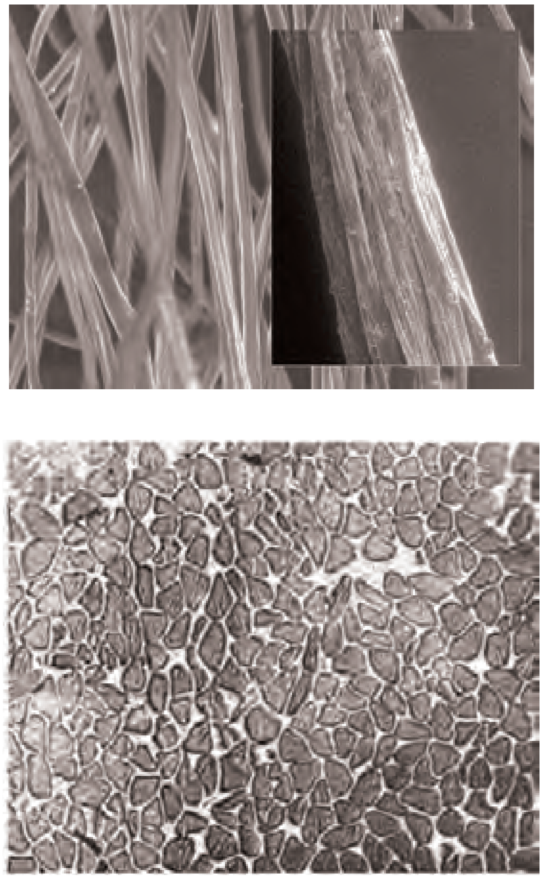


FIGURE 17. TOP: SILK FIBROIN FIBERS BEFORE AND AFTER EXTRACTION
BOTTOM: CROSS-SECTION OF SILK FILAMENTS [LEWIN, 2007]

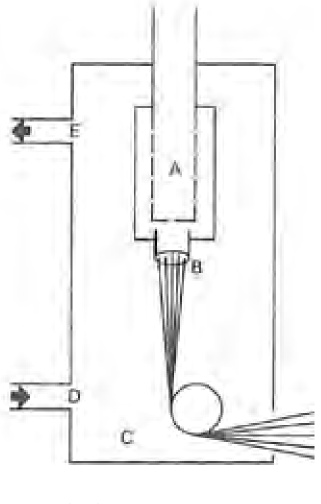


FIGURE 18. (L) SPINNERETS [Schrijnemakers and Schulte, 1985]

FIGURE 19. (R) DRY SPINNING PROCESS [Schrijnemakers and Schulte, 1985]

The first step in the fiber regeneration process is removing the lignin, which keeps the fibers together. This involves treating the wood pulp with caustic soda or an organic solvent. The viscous solution that results is spun in a spinning process. There are different spinning processes, one that is commonly used for the production of viscose is dry-jet wet spinning, while dry spinning is more common for the production of acetate. In all spinning methods, a spinneret is used to extrude the material through. Figure 18 shows two spinnerets [Schrijnemakers and Schulte, 1985]. The dry spinning process is schematically shown in Figure 19 [Schrijnemakers and Schulte, 1985]. At A, the viscous solution is pressed to the spinneret B through a filter. The area C is a dry room, in which hot air is fed at D to solidify the filaments. The air leaves the room at E to be purified.

The resulting filaments are either kept intact and used as filament fiber, or cut into smaller fibers and treated in order to change their properties. Viscose, Cupro, Acetate and Lyocell are all types of textiles that are made of regenerated cellulose.

Synthetic fibers

Synthetic polymers are used for the production of synthetic fibers. Acrylic, nylon and polyester are the three most produced synthetic fibers [Kajiwara, 2009]. They are preferred because of their low cost, good processability and performance [Lewin, 2007; Kajiwara, 2009]. In theory, it is possible to produce fibers from all polymers, since their performance depends mostly on the manner in which they are processed. The process for producing synthetic fibers is similar to that of regenerated fibers, in which molten polymer is fed through a spinneret.

5.4.3 FIBER PROPERTIES

Asides from the origin of fibers, there a number of properties that are important for fibers in order to use them for the production of textiles. These properties can be divided into dimensional, physical, mechanical and general properties.

Dimensional

The dimensional properties of fibers that are determinant for the quality of the textile are length, slenderness ratio (or fineness) and the shape of the cross-section. Lengthwise, it is important that the fibers are not shorter than 6-7 mm, in order to ensure they can be used in yarn production [Goswami, 2004]. Shorter fibers can be used in the production of non-wovens though.

Fibers typically have a length to diameter ratio of 100:1 [Callister, 2003]. Finer fibers are easier to bend, which translates into yarns with higher flexibility and fabrics with soft handle, graceful drape, flexibility and more luster, due to a greater reflection of incident light without distortions [Goswami, 2004]. The fineness also determines the number of fibers in the cross-section of the yarn [Goswami, 2004].

The cross-section of fibers has found to be related to certain properties of textiles [Goswami, 2004]:

- Circular cross-sections: good handle and feel, warmth-retaining properties;
- Ribbon-like cross-sections: greater coverage;

- Triangular cross-sections: more luster;
- Hollow fibers: good moisture absorption.

Physical
The physical properties of fibers that are important are the density and crimp. The density affects the weight and bulk of fabrics: a low density results in a fuller and bulkier appearance of the textile [Goswami, 2004]. Crimp is defined as the 'waviness' of the fiber, which enables the fibers to entangle with each other to create a yarn. The more the fibers are entangled, the stronger the yarn.

Mechanical
A number of mechanical properties determine the performance of the fiber and as a result the textile, such as the strength, elongation, elasticity, recovery and bending stiffness [Goswami, 2004].

General
Other factors that are important characteristics in fibers are friction, moisture and thermal characteristics. Friction is important because it is responsible for keeping together spun yarn, and for keeping woven yarns to maintain their position in the interlaced form. Low frictional coefficients lead to poor yarn strength due to slippage, high frictional coefficients hinder processing [Goswami, 2004].
Moisture and thermal characteristics are relevant for the wear-comfort of the resulting textile; water absorbing fibers help keep the skin dry and warmth retention helps keep skin temperature at an even level.

Some other factors that can influence textile characteristics are softness, durability, abrasion resistance and resistance to chemicals and UV [Goswami, 2004].

5.5 DESIRABLE TEXTILE PROPERTIES

Although there are many different types of textiles, they have a number of properties in common that make them suitable for use in garments. These properties can be divided into three groups: aesthetic, functional and comfort properties. Aesthetic properties relate to the appearance of the textile. Appearance is of great influence on the duration of use: once a garment loses its aesthetic appeal it is often disposed of. Common factors that negatively influence the appearance of textiles are tearing (abrasion resistance), pilling (pilling resistance) and bursting strength [Emirhanova and Kavusturan, 2008].

Functional properties relate to the function the textile has to fulfil; for garments this may be warmth retention or water resistance, but for technical textiles this could also be flame resistance and strength. Functional properties can in general be measured.

Comfort properties relate to the subjective perception of various sensations [Li, 2010], therefore they are highly subjective and complex. Some aspects related to comfort properties are [Li, 2010]:

- thermo-physiological comfort: which involves the transfer of heat and moisture through a fabric;
- sensorial comfort: the sensation felt when the textiles comes in contact with the skin;
- body movement comfort: the extent to which the textile allows freedom of movement;
- aesthetic appeal: the perception of the textile by all senses.

There is no consensus in literature as to what (combination of) properties are most important. Obviously, this will also differ for different textiles and functions. However, there is one property that can be seen as a requirement for textiles, which is flexibility. Without flexibility, it is not possible to create a wearable garment. Although this requirement seems obvious, it is often taken for granted as an inherent quality of textiles and therefore not discussed in literature related to comfortable textiles.

However, there are certain other properties that are often used when describing textiles, such as *drape*, *handle* and *softness*. Drape is defined as the graciousness with which a fabric hangs or drapes; a function of its resistance to bending and its own weight [Emirhanova and Kavusturan, 2008]. Handle or hand refers to the total of sensations that are experienced when a fabric is touched or manipulated by the hands [Altas, 2013]. It is related to properties such as flexibility, friction coefficient and surface properties. Softness can be described by three aspects: flexibility, compression and smoothness [Li 2010].

These properties can be present in textiles to different extents, depending on the function of the garment. For instance, a fabric with high drapability can be desirable for use in a dress, but it is not required when designing a blazer. Therefore, they should not be seen as requirements, but as means to describe the properties of textiles.

A list of desirable properties for textiles was composed from literature, as shown in Figure 20 [based on Li,

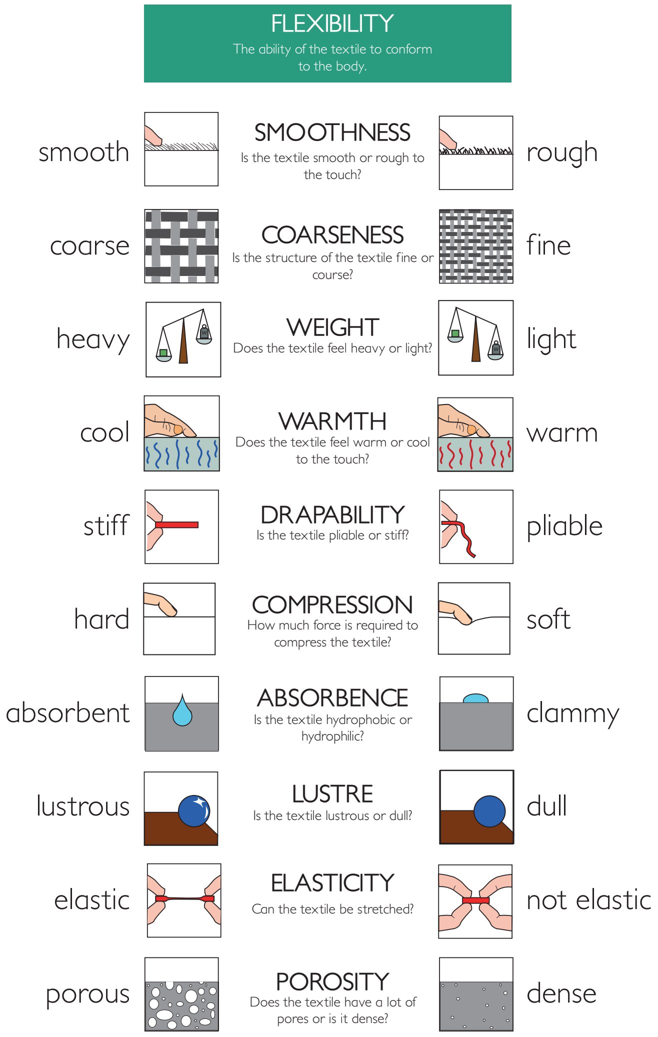


FIGURE 20. DESIRABLE PROPERTIES FOR TEXTILES [ADAPTED FROM KARANA, 2009]

2010; Karana, 2009 and Goswami, 2004]. Most of these properties or descriptors belong to the 'comfort'- group, since they are related to what people experience.
The properties are shown with their extremes (e.g. *drapability* has stiff and pliable as extremes), since both can be used to express a certain quality of a textile.
Not all of these descriptors are on the same 'level'; they can be subjective (*warmth*) or measurable (*elasticity*). However, studies have shown that also the measurable properties are used and understood by people to describe certain characteristics of a material [Karana, 2009] and therefore they are also included in this list. Since both handle and softness can be described in terms of other descriptors, such as flexibility, smoothness and weight, they are left out of the list.

This list of properties will be used throughout this thesis as a descriptive indication of the properties of (3D printed) textiles.

5.6 CONCLUSIONS

By analysing garments, it has become clear that textiles are more complicated than they would seem on first glance. Textiles are complex structures, influenced by a large number of factors. The properties of textiles are mostly obtained by their hierarchical structure. On each level, the characteristics of the chosen material, process or structure influence the final nature of the fabric. However, the production from fiber to final garment is extensive and consists of many steps, and for each step certain limitations occur, that are fed throughout the chain.

It is not possible to definitely say what properties a textile needs to have, in order to be used for garments. The only requirement is that the material needs to be flexible, in order to be able to conform to the body and leave room for movement. For the other properties, it was found that they depend heavily on the function the garment will have. For instance, denim and viscose are both textiles with very different properties, making them suitable for different applications (jeans or jackets versus T-shirts and undergarments). Therefore, the best application for a textile depends on its properties and vice versa. It is however possible to determine certain properties that can be used as descriptors for textiles (i.e. that can be used to describe certain characteristics of fabrics).
Looking into the materials that fibers are commonly made of, it can be seen that next to the natural materials, such as cotton, that we often associate textiles with, a large portion of possible fiber materials is occupied by synthetic materials, or polymers. These polymers are no different from the plastics that we encounter in our daily lives, but which are often associated with cheap, hard and rigid properties. The fact that embodied in textiles they are suddenly soft and flexible, can be attributed to their structure: the diameter to length ratio is large enough so that the material becomes soft and flexible. As such, it is difficult to recognize the base material in the end product; it is hard to imagine that a soft sweater can be made from the same base material as a food container for instance.

Therefore, it can be seen that it is better to describe textiles as a structure, than as a material. With current 3D printing technologies, it is difficult to mimic this structure and therefore the properties of textiles. This leads to the question if perhaps trying to imitate a woven or knitted structure is not the best strategy for 3D printing textiles, since these structures are the results of the optimization of a different manufacturing process. Thus, if the structure cannot be obtained by additive manufacturing as a process, the materials that are used could potentially replace this.

6. 3D PRINTED TEXTILES

6.1 3D PRINTED TEXTILES IN LITERATURE

3D printed textiles were first proposed by Evenhuis in 1999 [Freedom of Creation, 2006]. Instead of using continuous fibers in sheet-form, a material was produced that consisted out of individual links. Since then, the use of individual, plastic links for the production of 3D printed textiles has been generally accepted, although no formal definition has been established. Bingham et al. (2007) define 3D printed textiles as "micro- or meso-level free-moving assemblies produced in one manufacturing process". In another paper, Crookston et al. (2008) describe 3D printed textiles as "a large set of deformable, discrete, solid bodies with small feature sizes relative to the dimensions of the macroscopic assembly".

However, these definitions mostly describe a means of producing textile-like structures with rigid components, while there are also material considerations that might be included.

A classification of 3D printed parts for use in garments has been proposed by Mikkonen et al. (2013a). They distinguish six categories, based on the use of the part rather than the production process:

- Decorative components: components that are attached to fabric/garments, without having a technical function.
- Functional components: components that are attached to fabric/garments and have a technical function. Examples of this are zippers and other types of closures.
- Accessories: fully printed objects that are wearables, but not clothing, such as jewelry or bags.
- Fabric-like: a 3D printed part that behaves like a fabric and can be used as such. This differs from partial garments, in that it still needs to be altered into a different shape.
- Partial garment: almost a full piece of clothing, although it still needs some alterations. An example of this is printing pattern pieces that need to be put together after printing.
- Full garment: a ready-to-wear garment that is completely printed.

A material benchmark is used to find out what has already been done in the field of 3D printed garments, in order to position the materials relative to each other, to investigate potential application areas and to find emerging material experiences. The examples are shown on the following pages. Most of the materials used in these examples could be obtained as a sample, which is why it was possible to include the descriptors for their textile-like properties.

6.2 BENCHMARK

Drape dress by Freedom of Creation

The drape dress, created by Freedom of Creation, is made from a chainmail-like structure of interlocking rings. It is made out of nylon, and produced by means of Selective Laser Sintering.

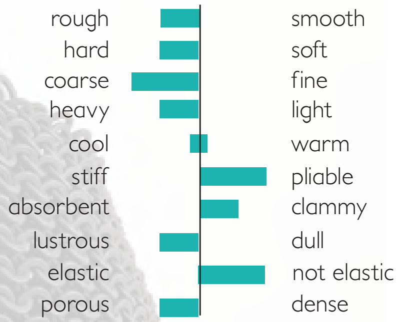


IMAGE SOURCE: FREEDOM OF CREATION

N12 by Continuum Fashion

This bikini was made by Continuum Fashion, from a material developed by Shapeways. The material consists of thousands of circular plates, connected by thin strings, which provides the material with certain flexibility. The placement of the circles in a pattern was achieved by written code, which takes the curvature into account in order to fill the surface [Continuum Fashion, n.d.]. It is made of white nylon and produced by means of Selective Laser Sintering.

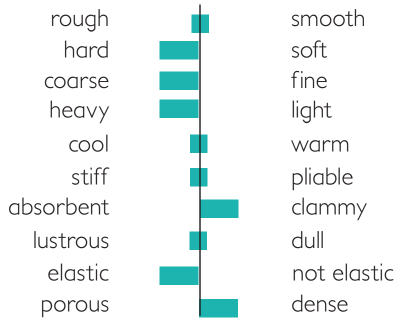


IMAGE SOURCE: CONTINUUM FASHION

In Bloom by XYZ Workshop

The In Bloom Dress by XYZ workshop is printed entirely with an Ultimaker Desktop printer and made of PLA. It is based on a standard sewing pattern, in which all the pattern parts are divided into smaller panels in order to fit onto the printer bed. The smaller panels are attached together using an adhesive. The very low thickness of the panels of 0.2 to 0.4 mm provides the structure with flexibility [XYZ Workshop, 2014].

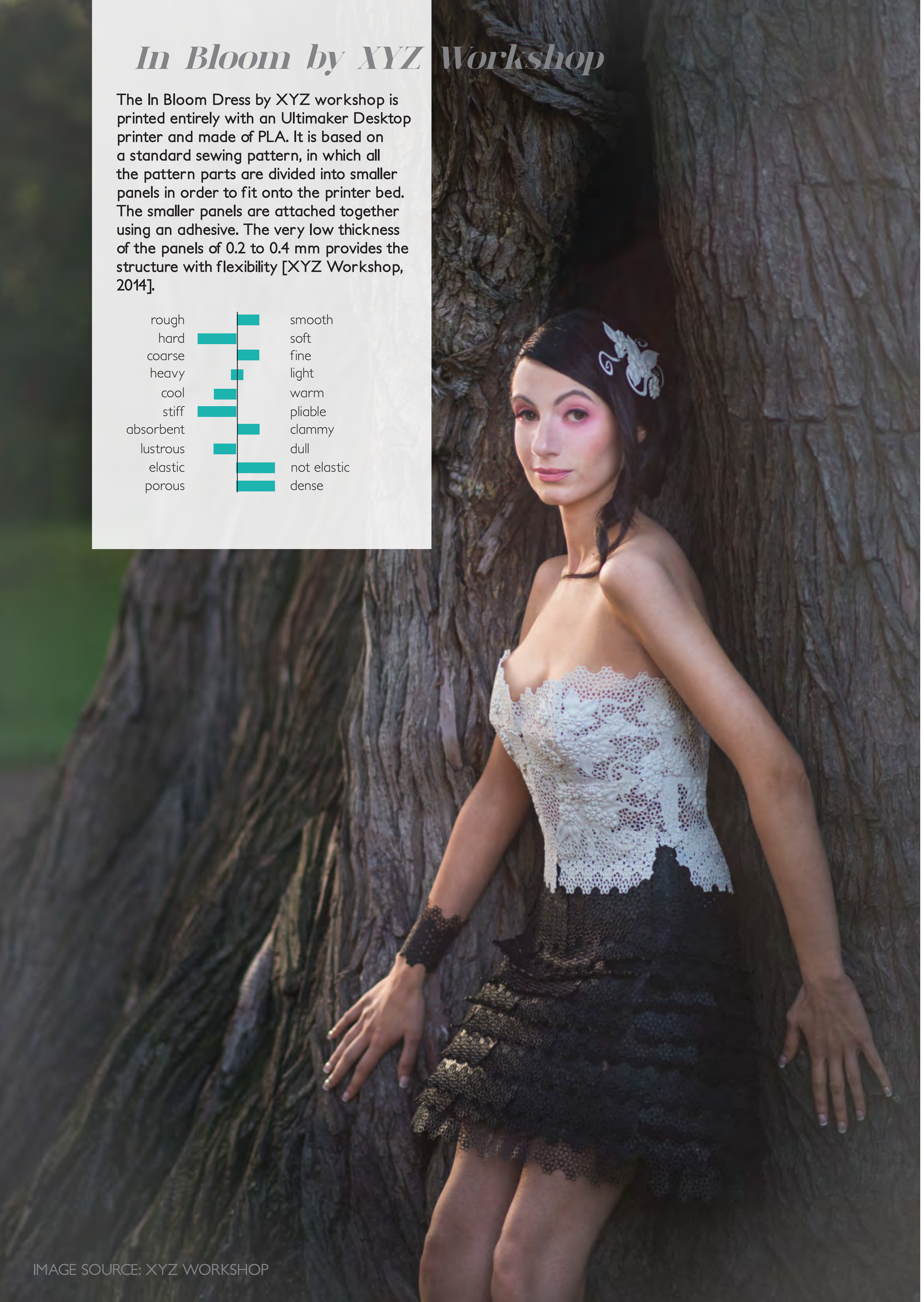
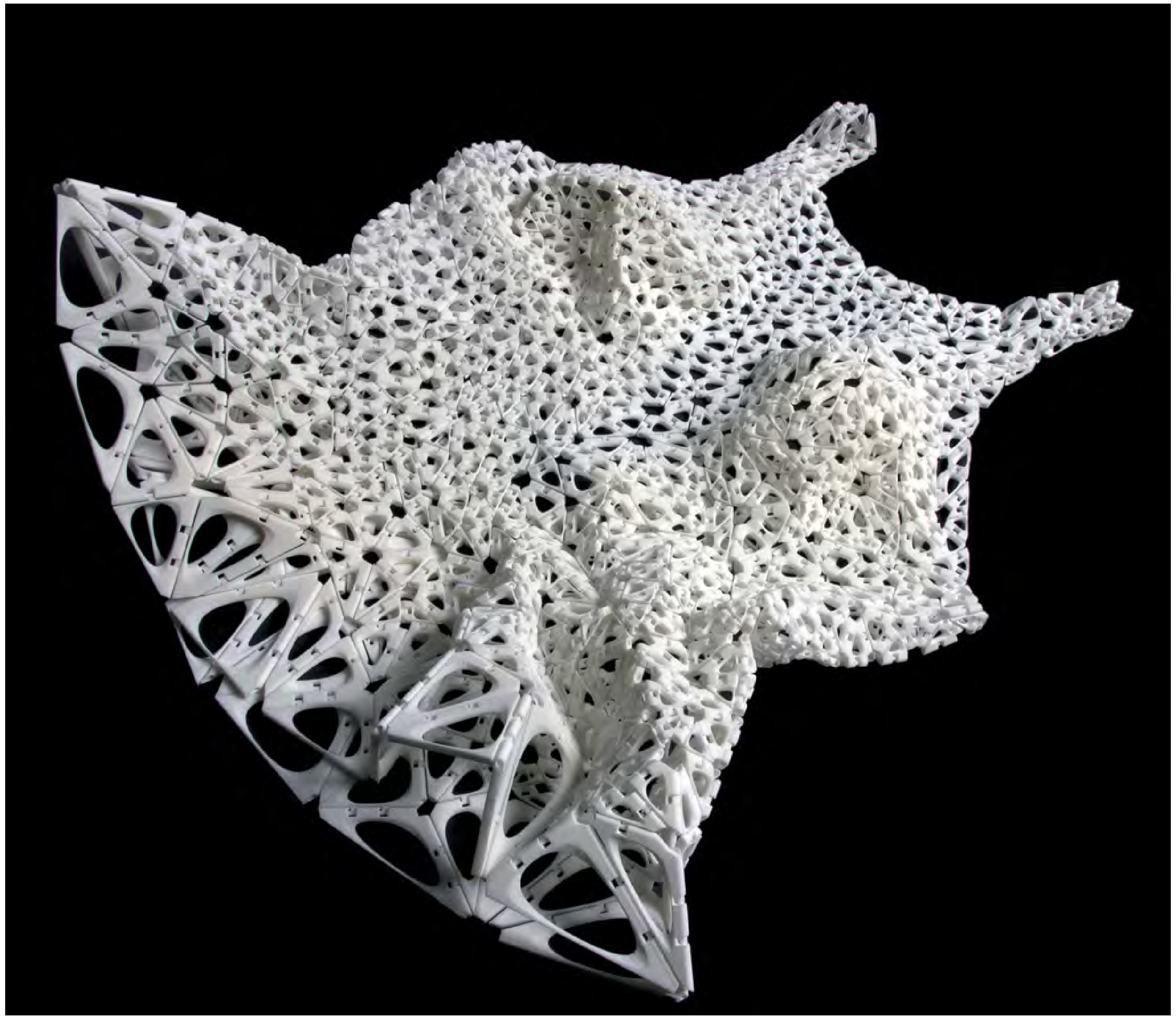
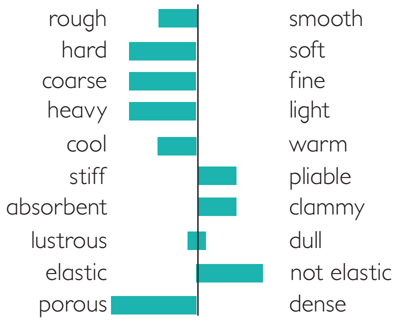


IMAGE SOURCE: XYZ WORKSHOP



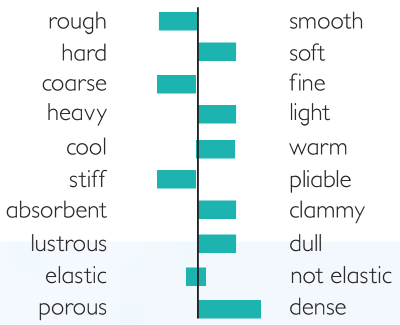
Nervous Systems

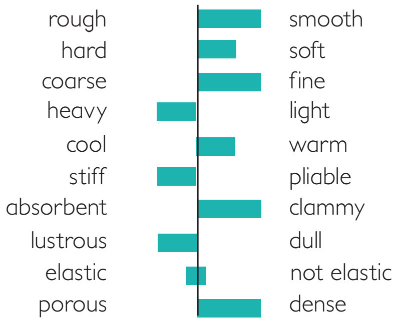


Nervous System has developed a type of software, called 'Kinematics', that is able to create surfaces of hinged panels and simulate a strategy to efficiently fold and compress these [Nervous Systems, 2014]. The bodice is comprised of 1,320 hinged pieces and 3D printed as a single part, with integrated closures on the back. It was printed by Shapeways, by means of SLS in nylon [Nervous Systems, 2014]. A 3D printed body scan served as a basis for the design.

Iris van Herpen

Iris van Herpen is probably the most famous fashion designer incorporating additive manufacturing into her designs. She has collaborated with Neri Oxman and Materialise to create complex, geometrical garments. This dress is produced by means of Selective Laser Sintering and is made of Materialise's flexible material TPU 92A-1, which is a thermoplastic polyurethane [i.materialise, 2014].



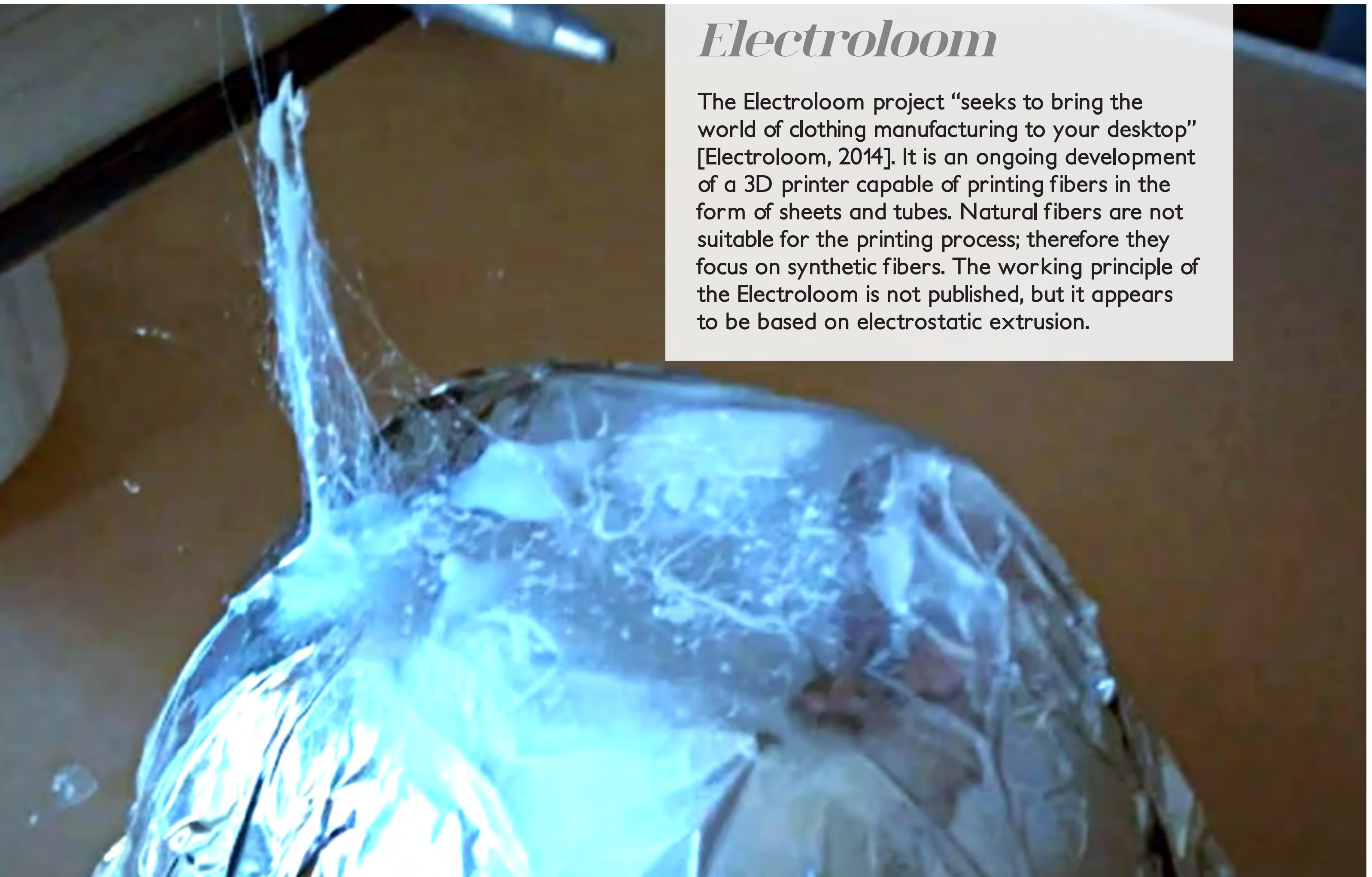


TangoBlack

This corset is the result of research conducted by Mikkonen et al. (2013b) at Aalto University, Helsinki. It is created on a multi-material PolyJet printer, with a material that is naturally flexible, called TangoBlack. The goal of the research was to treat the material as a regular fabric and creating a wearable piece of clothing out of it. The slits in the material were created to simulate a 'weaving direction'. The corset is printed in separate parts, which are connected by separately printed white connectors.

Tamicare

The Cosyflex material, developed by Tamicare, is produced by spraying a combination of elastomers and viscose fibers in layers onto a mould. The fibers are flocked by means of a high tension electrostatic generator, which causes the fibers to anchor vertically into a wetting agent [Giloh, 2012]. This fiber orientation makes the material soft to the touch. Elasticity is achieved by spraying the fibers with a thin layer of elastomer. However, it is unclear as to whether the process is driven by digital design files, which makes it uncertain whether it fits into the category of 3D printed textiles.



Electroloom

The Electroloom project "seeks to bring the world of clothing manufacturing to your desktop" [Electroloom, 2014]. It is an ongoing development of a 3D printer capable of printing fibers in the form of sheets and tubes. Natural fibers are not suitable for the printing process; therefore they focus on synthetic fibers. The working principle of the Electroloom is not published, but it appears to be based on electrostatic extrusion.

IMAGE SOURCE: FABRICAN LTD.

Fabrican

Better known as Spray-on Fabric, this material is an instant spray-able, non-woven fabric in a can. It consists of a liquid carrier in which short cotton fibers have been suspended [Fabrican Ltd, 2007]. By spraying it onto a surface, the cotton fibers adhere to each other and create a thin, non-woven fabric. The technology has been patented, and so far it has not yet been commercially available.

IMAGE SOURCE: OPENKNIT

OpenKnit

OpenKnit is an open-source initiative for the creation and distribution of digital files that can be produced with a knitting machine. The use of a knitting machine is described as the first form of 3D printing clothing, which is in definition true, since it is an additive technology that is driven by digital design files. The knitting machine itself can be built for less than €550 [OpenKnit, n.d.], although not many patterns are available yet.

Silk Pavilion

The Silk Pavilion is an exploration by MIT Media Lab, designed by prof. Neri Oxman, about the relationship between digital and biological fabrication [Oxman et al., 2013]. A primary structure was created out of polygonal panels made of silk threads. Silkworms were deployed as biological 3D printers, to create a secondary structure on top of this, which resulted in a dome with variations in density. The goal of the project was to research the natural process of silkworms building their cocoons, in order to develop ways in which architectural structures can be printed more efficiently.

IMAGE SOURCE: MIT MEDIA LAB

6.3 BENCHMARK OVERVIEW

The products shown on the previous pages are compared to each other to find emerging material experiences and potential application areas. They are shown in Table 03 below. The table shows the materials that were used for the benchmark in the columns. The application area is shown underneath. For each material, the most important functional, experiential and sustainable issues are listed, followed by other trends relevant to the field.

6.4 CONCLUSIONS

This chapter has reviewed the literature that was available on 3D printed textiles, and given an overview of what has been done regarding 3D printed garments.

The benchmark has not included other wearables, such as jewellery and accessories, since the focus is on designing a textile. If this category were included, many more examples could have been shown. Within the category garments, it can be seen that most application areas are dresses, tops, underwear (corsets) and swimwear (bikini).

The benchmark overview has shown that the experiential qualities of some materials are suitable for textiles. However, the functional qualities of the materials are not yet sufficient.

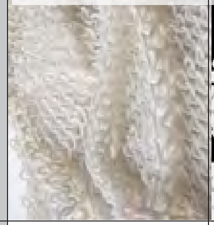
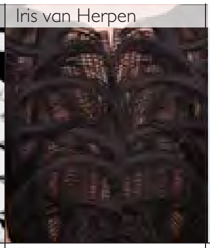
	Freedom of creation	Continuum Fashion	Iris van Herpen	Nervous System	Xyz Workshop	TangoBlack/Aalto
						
Type	Multiple assembly Nylon SLS	Thin structure Nylon SLS	Flexible material Polyurethane SLS	Multiple assembly Nylon SLS	Thin structure PLA FDM	Flexible material Acrylic PolyJet
Applications	Dress Bag	Bikini	Dress	Dress Top	Dress Top	Corset
Functional qualities						
Machine washable	no	no	yes	no	no	unknown
Breathability	high	medium	low	medium	low	low
Absorbence	medium	medium	low	medium	low	low
Uv-resistance	low	low	low	low	low	low
Elasticity	low	medium	medium	low	low	low
Drapability	high	medium	low	medium	low	low
Experiential qualities						
Delicateness	medium	high	low	medium	high	low
Softness	low	low	high	low	low	high
Smoothness	low	high	high	high	high	high
Warmth	low	low	medium	low	low	medium
Lustre	medium	medium	low	medium	high	high
Sustainable issues						
Recyclable	no	no	yes	no	yes	no
Biodegradable	no	no	no	no	yes	no
Renewable	no	no	no	no	yes	no
Durability	high	low	unknown	high	high	low
Other emerging issues	Ready-to-wear	Ready-to-wear	Haute couture	Conceptual	Haute couture	Conceptual

TABLE 03. MATERIAL BENCHMARK OVERVIEW

PART II

MATERIAL CHARACTERIZATION

In this part, 3D printed textiles as a material are further explored. By means of the findings of the previous section, a classification and definition of 3D printed textiles are proposed. The influence of material, structure and process on the resulting material is discussed in a technical characterization of 3D printed textiles, including a life cycle analysis of two types of 3D printed textiles found in the benchmark to indicate their sustainable impact. Four samples are used for an experiential characterization.

Consequently, a number of samples that have been created throughout the project are presented, and discussed by means of their technical and experiential characteristics and design options. Finally, the findings from the (obtained) samples and tests are discussed.

7. 3D PRINTED TEXTILES


FIGURE 21. MULTIPLE ASSEMBLIES WITH DIFFERENT PATTERNS BY FREEDOM OF CREATION

7.1 CLASSIFICATION

A distinction can be made between three types of 3D printed textiles, which was based on analysis of the benchmark and a number of tests: those basing their flexibility on structure, those basing their flexibility on the material, and a combination of the two. This is visualised in Figure 22 Their characteristics are used to create an overlapping definition of 3D printed textiles: 3D printed flexible, textile-like structures.

7.1.1 STRUCTURE-BASED

3D printed textiles that base their flexibility on structure, are classified as structure-based 3D printed textiles. Multiple assemblies are an example of this category. Problems associated with multiple assemblies include [Hague, 2006]:

- Limitations in CAD systems: the generation of large data sets, wrapping links over complex surfaces, collapsing the structure for efficient manufacturing;
- The resolution of the additive manufacturing process;
- Design of the links: 'buckling' of links can be a problem.

However, using an assembly of links also has certain advantages. The structure enables the production of a flexible sheet or product, made out of a rigid material. Also, due to the geometric possibilities provided by additive manufacturing, the links can be made into virtually any shape, to create patterns (some examples are shown in Figure 21) or to create differences in drape characteristics and freedom of movement [Bingham et al., 2007].

Multiple assemblies exist in different forms, such as assemblies of links or integrated hinges. They are very suitable to be created by means of additive manufacturing processes, although not all processes can be used. Selective Laser Sintering (SLS) and Stereolithography (SLA) have been the most common used processes. These are most suitable due to their high resolution and inherent support. Fabric-like materials made with these processes have been created by Shapeways and Materialise among others, and are discussed later on in this chapter. Fused Deposition Modeling (FDM) can also be used to some extent, although there are more limitations in link design for this process.

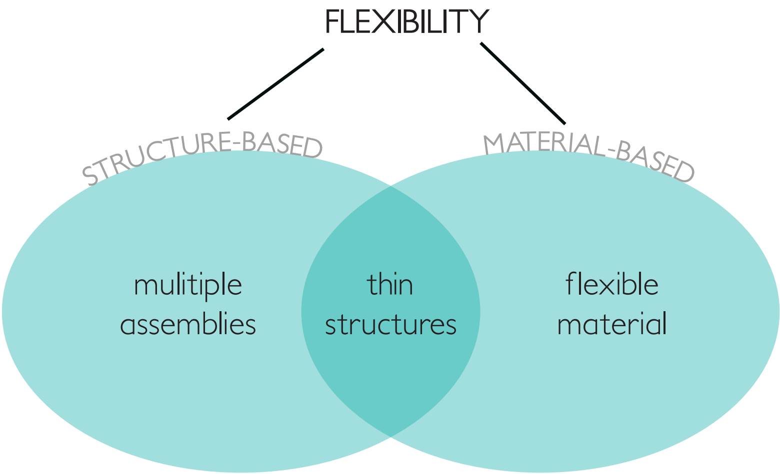


FIGURE 22. CLASSIFICATION OF 3D PRINTED TEXTILES

7.1.2 MATERIAL-BASED

Although multiple assemblies are currently the largest part of the 3D printed textiles market, there is also potential for them on more material-related principles. The flexibility of these 3D printed textiles is obtained by the characteristics of the (base) material, rather than by the structure.

A lot of flexible materials are at the moment being developed for 3D printing. Flexible, rubber-like materials are now available for SLS, FDM and PolyJet technology. The biggest disadvantage of these materials is that they are quite weak (not tear-resistant) and often difficult to print with good results.

Most flexible materials are more resembling of rubber than of fabric: they are not soft or air-permeable. Therefore, in order to create a comfortable fabric-like material, they require some kind of structural enhancement to obtain these properties. For instance, Mikkonen et al. (2013b) have created a corset out of a flexible PolyJet material (TangoBlack) and made it air-permeable by creating slots into a flat sheet.

7.1.3 THIN STRUCTURES

An overlapping category can be distinguished which uses both material- and structure-based principles, named thin structures. Thin structures have not yet been applied a lot as 3D printed textiles. As with flexible materials, they can be produced as one part, however they require a special structure to impart them with flexibility. Examples of this are very thin sheets of plastics, which are flexible because of the thin structure they have, but also because the material has some inherent flexibility. Polymers and metals are good examples of materials that allow themselves to be used for thin structures.

One example of thin structures applied as 3D printed textiles is used in the In Bloom dress by xyz studio, discussed on page 38, which consists of very thin, printed panels. Another example is the Honeycomb material developed by Shapeways, which is more extensively discussed in chapter 8.5 and consists of hexagonal shapes that are connected to each other by tiny springs.

7.2 CONCLUSIONS

As has been discussed before, the main requirement for textiles (traditional as well as 3D printed) is flexibility. This is important for garments, since they are worn close to the body and are even seen as an extension of the body [Gemperle et al., 1998], which is always active and dynamic. The other properties of textiles that are important for comfort (as discussed in chapter 5.5), can be present in textiles to different extents, depending on their function, therefore these properties are used as a measure to describe the 3D printed textile and to determine its function, rather than as a boundary definition.

Based on the aspects of 3D printed textiles described above, the definition that was chosen is

flexible, textile-like 3D printed structures.

Flexibility is an important aspect, since this is the main requirement for comfortable garments; it should be able to conform to the human body. *Textile-like* refers to the fact that it must behave like a textile, in that it must be able to form clothing-like structures, but also that there may be room for it to be not necessarily categorized as a textile. In practice, this will mean that it should be possible to form as a sheet or a 'hollow' product. Finally, *structure* is used as a term to describe all types of forms and hierarchies.

8. MSP DECONSTRUCTION

In the previous chapter, three important factors that influence 3D printed textiles have been identified: material, structure and process. In this chapter, the influence of these three factors is explored further, by means of a technical characterization of 3D printed textiles, which describes the way these three factors influence each other. In addition, a number of samples that were obtained are analysed for their experiential characteristics. The experiential characterization helps understand what the unique qualities of the material are on a sensorial, meaning and emotional level.

8.1 MATERIAL, STRUCTURE & PROCESS

3D Printed textiles are classified as a semi-developed material; a novel material of which the boundaries have not yet been determined. Just as with traditional textiles, they actually refer to a group of materials, with a range of different possible characteristics (rather than a specific material).

As shown by the classification of 3D Printed textiles, there are three factors that influence their properties: material, structure and process. These three factors also influence each other, and are therefore all important to the outcome of the final material.

The process is inherent to the material and structure, since the characteristics of the process determine which materials and structures can be used. Material and structure influence each other as a function of flexibility: hard materials require a different configuration to obtain flexibility than soft materials.

Since it was found that all three factors are important to the resulting 3D printed textile, this combination of factors will be referred to as MSP (material, structure, process), to distinguish between the use of the word *material* in its literal sense and as reference to a combination of aspects.

8.2 TECHNICAL CHARACTERIZATION

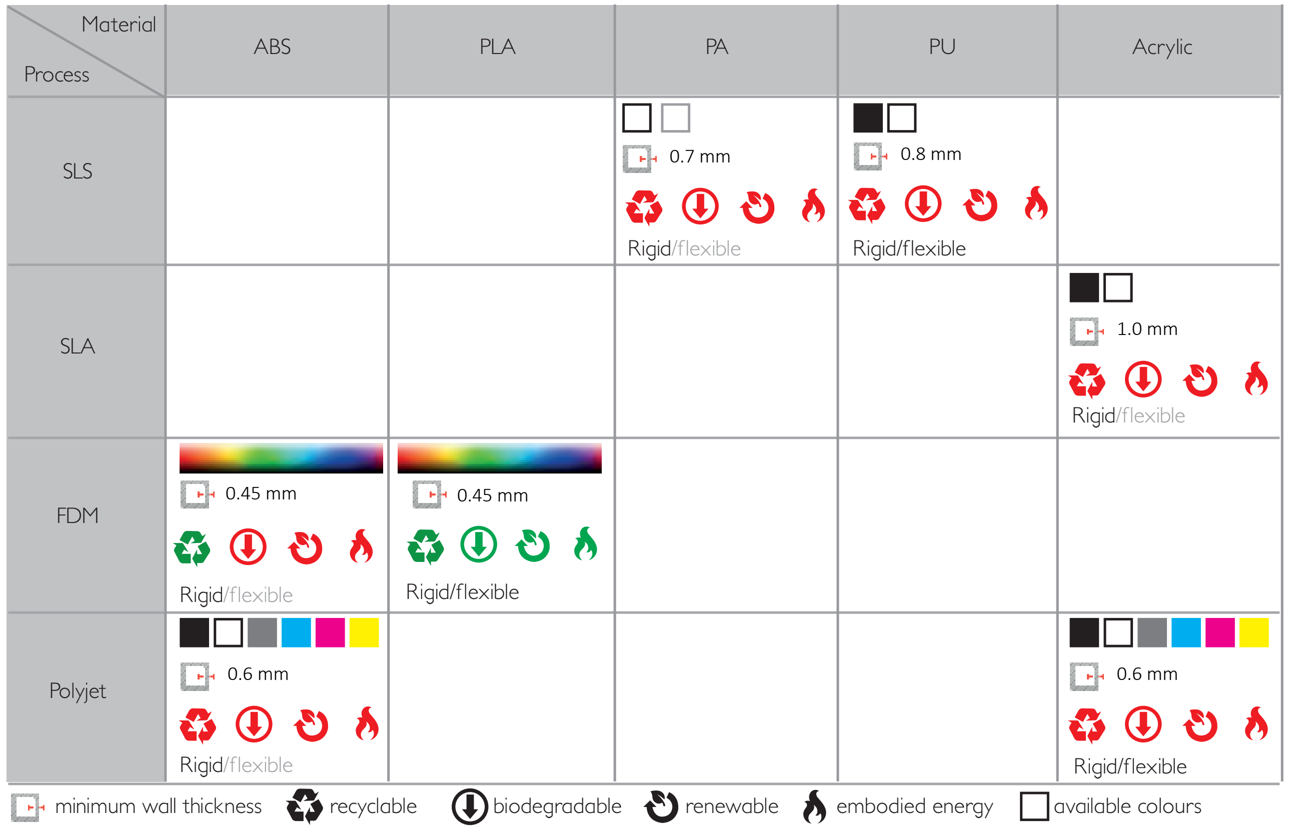
8.2.1 MAIN TECHNICAL PROPERTIES

The main technical property of all 3D printed textiles is flexibility, as is previously discussed. Per definition, flexibility is the complementary concept of stiffness – therefore the less stiff the material, the more flexible it is. As a result, it is possible to recognize varying degrees of flexibility in the 3D printed textiles. It is important to realize that the flexibility is largely influenced by the structure; for instance the chainmail-like structure of Freedom of Creation is more flexible than TangoBlack as a flat sheet. It is not necessarily true that the more flexible MSP's are better suited as textiles; this depends on their application. After all, knit jersey and denim have a different flexibility, but are both widely used as textiles in different applications.

What also can be seen from the examples shown in the previous chapter is that some MSP's have a large macro-structure, which allows the material to be more breathable. This is an important attribute in textiles, as was found in chapter 5. In addition, this structure allows water to escape through the material.

8.2.2 MATERIALS

Different materials can be used to produce 3D printed textiles. Currently, only plastics have been used, more specifically nylon (PA), polyactic acid (PLA), acrylonitril-butadieen-styreen (ABS), polyurethane and (photo-)acrylic. Table 04 shows these materials in relation to the printing processes with which they can be processed, along with a number of properties that are most influential of the performance of the printed parts (colour, minimum wall thickness, available stiffness and environmental properties). Additionally, Figure 23 shows the shore hardness of these materials.



Process \ Material	ABS	PLA	PA	PU	Acrylic
SLS			□ □ ⊡ 0.7 mm ♻ ⬇ ↻ 🔥 Rigid/flexible	■ □ ⊡ 0.8 mm ♻ ⬇ ↻ 🔥 Rigid/flexible	
SLA					■ □ ⊡ 1.0 mm ♻ ⬇ ↻ 🔥 Rigid/flexible
FDM	▬ ⊡ 0.45 mm ♻ ⬇ ↻ 🔥 Rigid/flexible	▬ ⊡ 0.45 mm ♻ ⬇ ↻ 🔥 Rigid/flexible			
Polyjet	■ □ ■ 🟦 🟪 🟨 ⊡ 0.6 mm ♻ ⬇ ↻ 🔥 Rigid/flexible				■ □ ■ 🟦 🟪 🟨 ⊡ 0.6 mm ♻ ⬇ ↻ 🔥 Rigid/flexible

⊡ minimum wall thickness ♻ recyclable ⬇ biodegradable ↻ renewable 🔥 embodied energy □ available colours

TABLE 04. MATERIAL VS. PROCESS CHARACTERISTICS

It can be seen that the used materials have very different properties, that determine the way in which the material can be used to create flexible structures.

Most materials have poor UV-resistance, especially the ones that are cured by UV-light (SLA and PolyJet). This means the life span of a garment that is worn outside could be significantly reduced, by alterations in aesthetics as well as mechanical properties, although this is also true for traditional textiles.

8.2.3 STRUCTURE

The structure is important to the final outcome of the MSP. As was shown in the classification of 3D printed textiles, different material-combination structures result in different classes of the material. It is difficult to say which structures are suitable or unsuitable for 3D printed textiles, since this depends on the function of the textile and the material. However, the applied structure is either responsible for providing flexibility (in the case of structure-based MSP's) or to not hinder flexibility (in the case of material-based MSP's). More structural solutions are explored in the tests described in chapter 9.

8.2.4 PROCESS

Virtually all AM processes can be used to produce 3D printed textiles. The choice of process influences the final outcome of the MSP in terms of the possible materials that can be used, the finishing of the textile and geometry (e.g. wall thickness, resolution).

8.2.5 CONSTRAINTS

The possibilities for 3D printed textiles are limited by the parameters of the 3D printing process. It was found by means of a number of explorations that the smaller the macro-structure of the material, the more it resembles a regular textile. Currently, the scale of the structure is limited by the possible minimum wall thickness that is allowed by the material and process (shown in Table 04).

Also, there are a limited number of materials available. All materials that have been used so far for 3D printed garments are plastics. This is not a strange choice for textiles, since a lot of fibers are made of synthetic polymers (as discussed in chapter 5.4). However, currently there is no possibility to print natural materials, such as cotton and wool.

Lastly, since the additive manufacturing processes that exist today were not developed with the specific goal to produce textiles, it is hard to say whether these are the ideal processes.

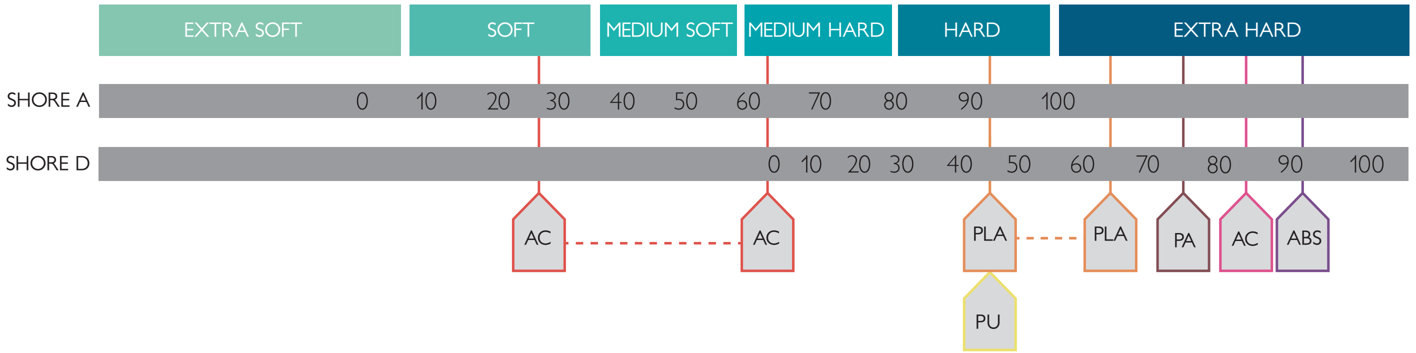


FIGURE 23. SHORE HARDNESS OF MOST COMMON MATERIALS

8.3 LIFE CYCLE ANALYSIS

The goal of this life cycle analysis (LCA) is to provide insight into the environmental burden of textiles (or textile-like materials) produced by means of additive manufacturing (AM). The outcome will be compared to traditional methods of producing textiles, such as weaving and knitting. The more detailed version of this LCA can be found in appendix D1.

Two types of 3D printed textiles from the benchmark were chosen to be analysed: the multiple assemblies created by Freedom of Creation (discussed on page 36) and the flexible material from Tamicare (discussed on page 42).

8.3.1 SYSTEM

The chosen functional unit is 1 kg 3D printed textile.
The scope of this assessment is cradle-to-grave. In the two cases described above, the product is produced at a company (local production), after which it has to be transported to the consumer.

The system for Scenario 1 is shown in Figure 24. The textile is made of PA2200 (nylon) by means of Selective Laser Sintering (SLS), for which the material is required to be in powder-form, and finished by means of industrial tumbling [Freedom of Creation, 2006]. The following data is available on the SLS process [Telenko, 2010]:

- SLS has a build density of approximately 30%, meaning that an input of 100 kg of powder will result in 30 kg of product;
- Of the left-over powder, approximately 90% can be reused in the process, the other 10% is waste;
- In order to create a qualitative product, the input must consist of at least 30% virgin powder.

For this situation, that means that approximately 3.5 kg of powder is required, of which 1 kg will result in the finished product, 0.25 kg will be waste and 2.25 kg will be available for recycling. This means that 1.25 kg of virgin powder is required as input. This is shown in the close-up in Figure 24. Since the recycling of powder is internal in the process, it is not taking into account in the LCA. The product is produced in Amsterdam and shipped to a user in The Netherlands.

The system for Scenario 2 is shown in Figure 25. The input materials are viscose fibers and natural rubber, which are layered onto a mould by means of spray depositioning (Figure 26) [Material ConneXion, 2014]. The manufacturing line is located next to Tamicare headquarters in Heywood, UK. It is shipped to a user in The Netherlands by aircraft. The product is a disposable product; it is thrown away after one use.

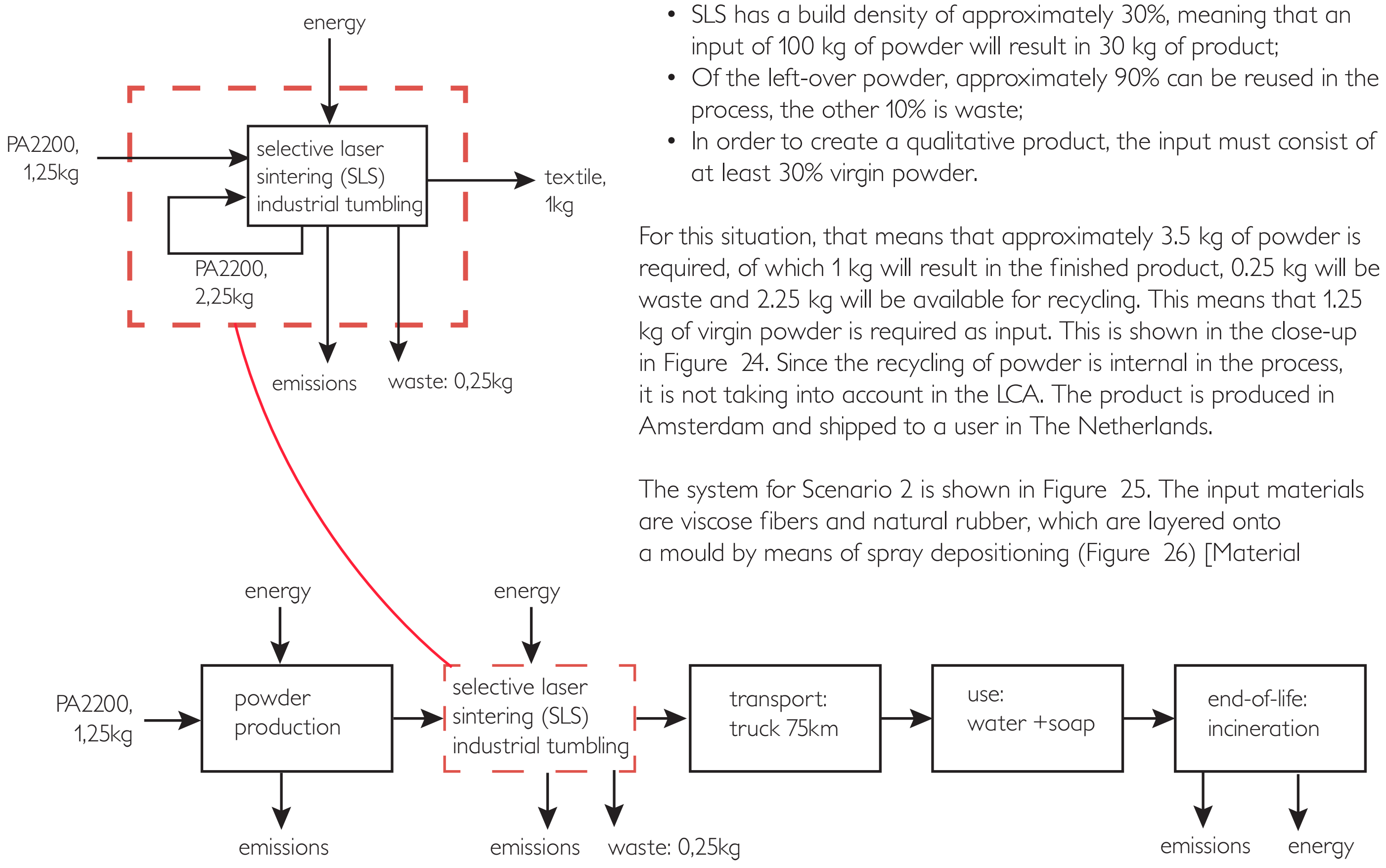


FIGURE 24. SYSTEM FOR SCENARIO 1

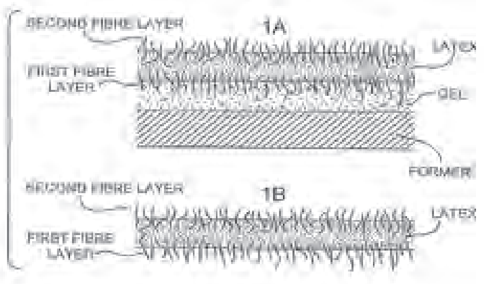


FIGURE 26. STRUCTURE OF COSYFLEX [GILOH, 20120]

8.3.2 ASSUMPTIONS

The following assumptions have been made in order to execute the LCA. A more detailed explanation is described in appendix D.

- The use phase is assumed to have an impact of less than 1%, since neither product is meant to be washed in the washing machine, and is therefore left out of this LCA.
- In the second scenario, the textile is assumed to consist of equal parts viscose and natural rubber.
- The average transport distance within the Netherlands is 75 km by truck.
- It is assumed that both products (eventually) end up in municipal waste.

8.3.3 RESULTS

The eco-costs of both scenarios are shown in Figure 27 and Figure 28. The more detailed LCA file can be found in Appendix D. The total eco-costs of the first product are €6.81. The largest proportion of the costs is determined by the material (32%) and SLS process (54%).

The total eco-costs of the second product are €34.16. Almost all of the costs are determined by the production process: 98%.

It is noticeable that for both scenarios transportation has a negligible effect on the total eco-costs. Localized production has indeed been identified as one of the benefits of 3D printing, regarding environmental impact, as well as absence of (a lot of) waste materials during production, which can also be seen in the figures.

8.3.4 COMPARISON

It is a common assumption that the use-phase is the most influential regarding the environmental impact of clothing, however it was shown by Van der Velden et al. (2013) that this is not actually the case. Instead, it was shown by a number of life cycle assessments that actually the manufacturing stage is the most influential. Regardless, most important for the production of garments is that

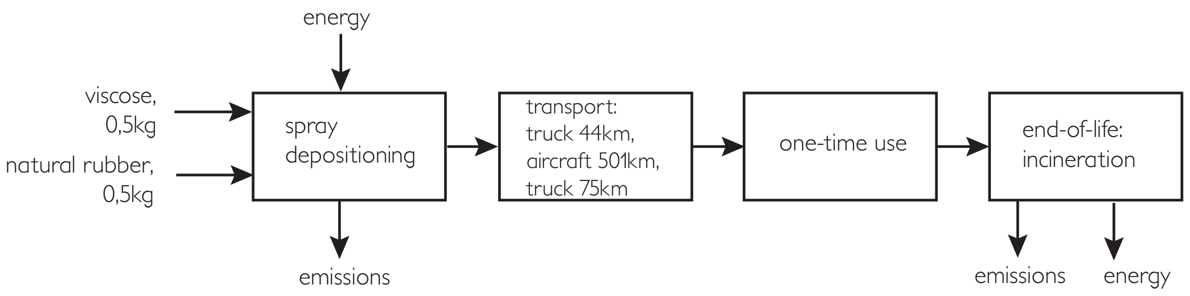


FIGURE 25. SYSTEM FOR SCENARIO 2

the right fabric specifications are chosen, which should always take into considerations the intended design and quality of the garment [Van der Velden et al., 2014].

The eco-costs for woven fabrics are shown below. It should be noted that the yarn thickness is one of the most important factors in calculating the eco-costs [Van der Velden et al., 2014]. Figure 29 shows the eco-costs of 1 kg of woven textile product with a yarn thickness of 70 dtex. The eco-costs for different materials range between €5 and €7. In Figure 30, the eco-costs for the same materials are shown for a yarn thickness of 300 dtex; in this case the eco-costs range from €3.50 to €5.

The eco-costs for the SLS process are comparable to those of a regular nylon textile with a yarn thickness of 70 dtex: €6.81 and €6.40, respectively. From both figures, it can be seen that nylon as a base material has a large impact on the total eco-costs (30-40%).

It should be remarked that dyeing and finishing also have a large impact on the eco-costs of woven textiles. In both 3D printing scenarios dyeing is not included; since this is not the case for both products at the moment. However, it is not unimaginable that in the future both products will also be dyed to create a range of different colours, which would also increase the eco-costs of the scenarios.

8.3.5 ECO-DESIGN STRATEGY WHEEL

In Figure 31, the product for scenario 1 and scenario 2 are mapped out in the eco-design strategy wheel. The product for scenario 1 scores rather well, improvements can be made for the production technique (which requires a lot of energy) and the end-of-life. The product for scenario 2 scores worse, mainly due to the production technique, the life span of the product and the alternative function. It also scores worse on distribution and transport, since this product needs to be shipped from the UK. Improvements could be made by prolonging the life span and reducing the energy required for the production process.

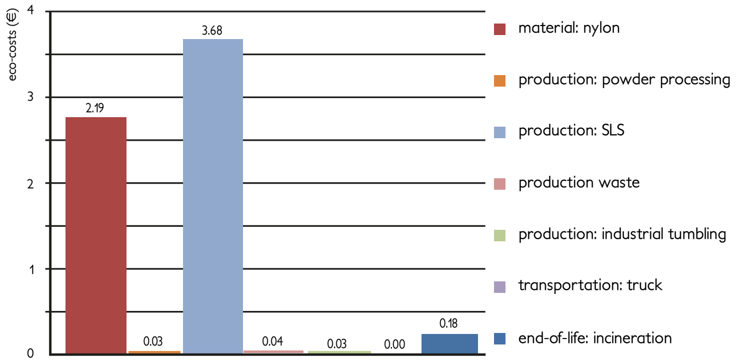


FIGURE 27. RESULTS FOR SCENARIO 1

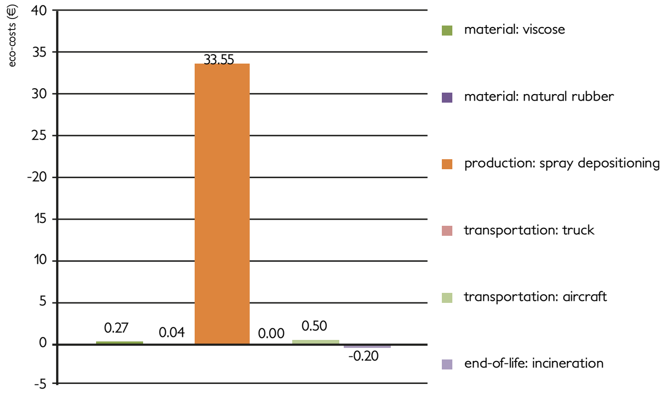


FIGURE 28. RESULTS FOR SCENARIO 2

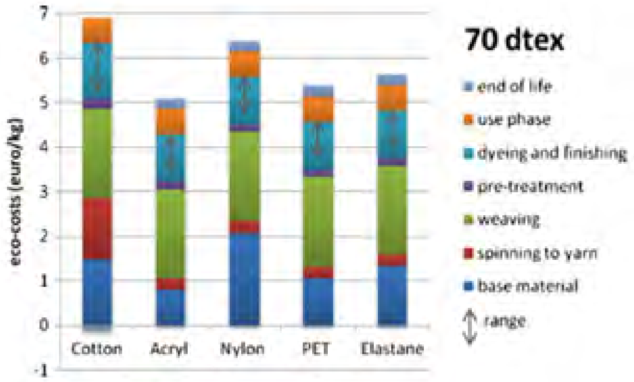


FIGURE 29. ECO-COSTS FOR 1 KG OF WOVEN TEXTILE YARN THICKNESS = 70 DTEX [VAN DER VELDEN ET AL., 2014]

FIGURE 30. ECO-COSTS FOR 1 KG OF WOVEN TEXTILE, YARN THICKNESS = 300 DTEX [VAN DER VELDEN ET AL., 2014]

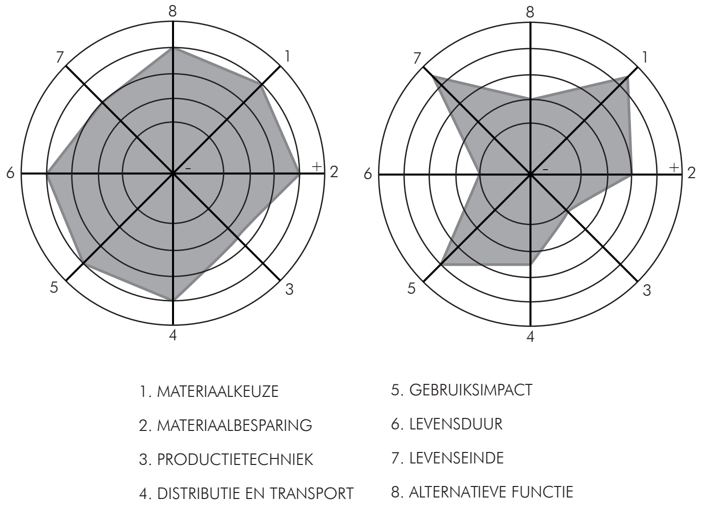
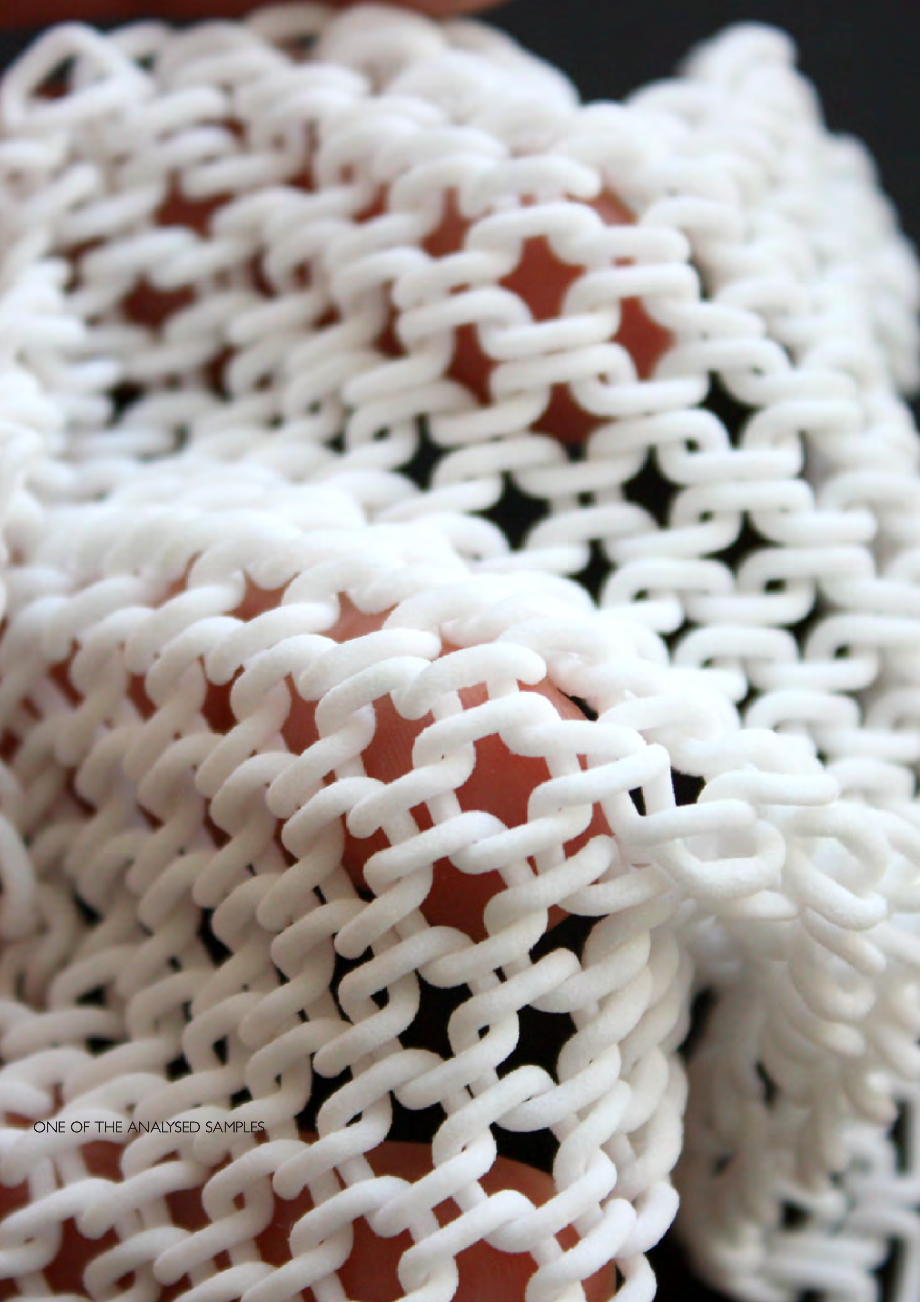


FIGURE 31. ECODESIGN STRATEGY WHEEL FOR SC.1 (LEFT) AND SC. 2 (RIGHT)



ONE OF THE ANALYSED SAMPLES

8.4 THE MATERIAL EXPERIENCE

Materials in product design have more functions than merely the use of their technical properties. More than anything, they are responsible for the expressive characteristics of the product; materials appeal to the user's senses and contribute to the meaning of a product [Karana, 2009].

The material experience is a term used to refer to the experience people have with the material of a product [Karana et al., 2008]. It manifests itself in the fact that a material can provide a different experience for people in one product application than in another. In the same manner, one product application can provide different experiences by the use of different materials. The material experience can be described as the effects that result from the interaction between the user and the material in a certain context [Karana et al., 2008]. There are three experiential components that can be distinguished in this experience, and that are used by people to describe materials [Karana et al., 2008]:

- the sensorial experience (how the material looks and feels);
- the experience of meaning (what the material expresses or elicited associations);
- the emotional experience (how it makes the user feel).

These factors all depend on context and time and can influence each other. By understanding the experiential components of a material, together with their functional and performance-related properties, it is possible to find unique and meaningful product applications [Karana et al., 2008].

In this chapter, the material experience of 3D printed textiles is explored by gaining an understanding of the material, on both a technical and a sensorial level.

8.5 EXPERIENTIAL CHARACTERIZATION

In order to explore the sensorial properties of the material, some samples were shown to a small number of participants. The goal was to find out the unique sensorial properties of the material, pleasing or unwanted characteristics and to observe the interaction people have with the material. The samples are shown in Figure 32.

8.5.1 SENSORIAL EXPERIENCE

The aesthetics of the materials was the most noticeable and pleasing characteristic, especially for the chainmail-like materials. These materials consisting of multiple assemblies are not that commonly found in daily life, which makes it a surprising material to feel. The organized, repeated pattern makes it also somewhat hypnotic to look at when moving it.
Due to their flexibility, it is easy to move the materials and play with them. This makes it inviting to bend and stretch them, trying to investigate their limits. The large chainmail-like structure lends itself to be thrown around in the hands or spread on a surface. The same goes for the smaller chainmail-like structure, although this material feels a little softer and more delicate, making it more suitable to 'caress' the hands with.

Some of the samples also make a noise when moved. Although this is not perceived as a negative issue when playing around with the samples, it is possible that this becomes a hinder when applied in a garment that is worn for an entire day (comparable to wearing a tinkling bracelet for instance).

8.5.2 EXPERIENCE OF MEANING

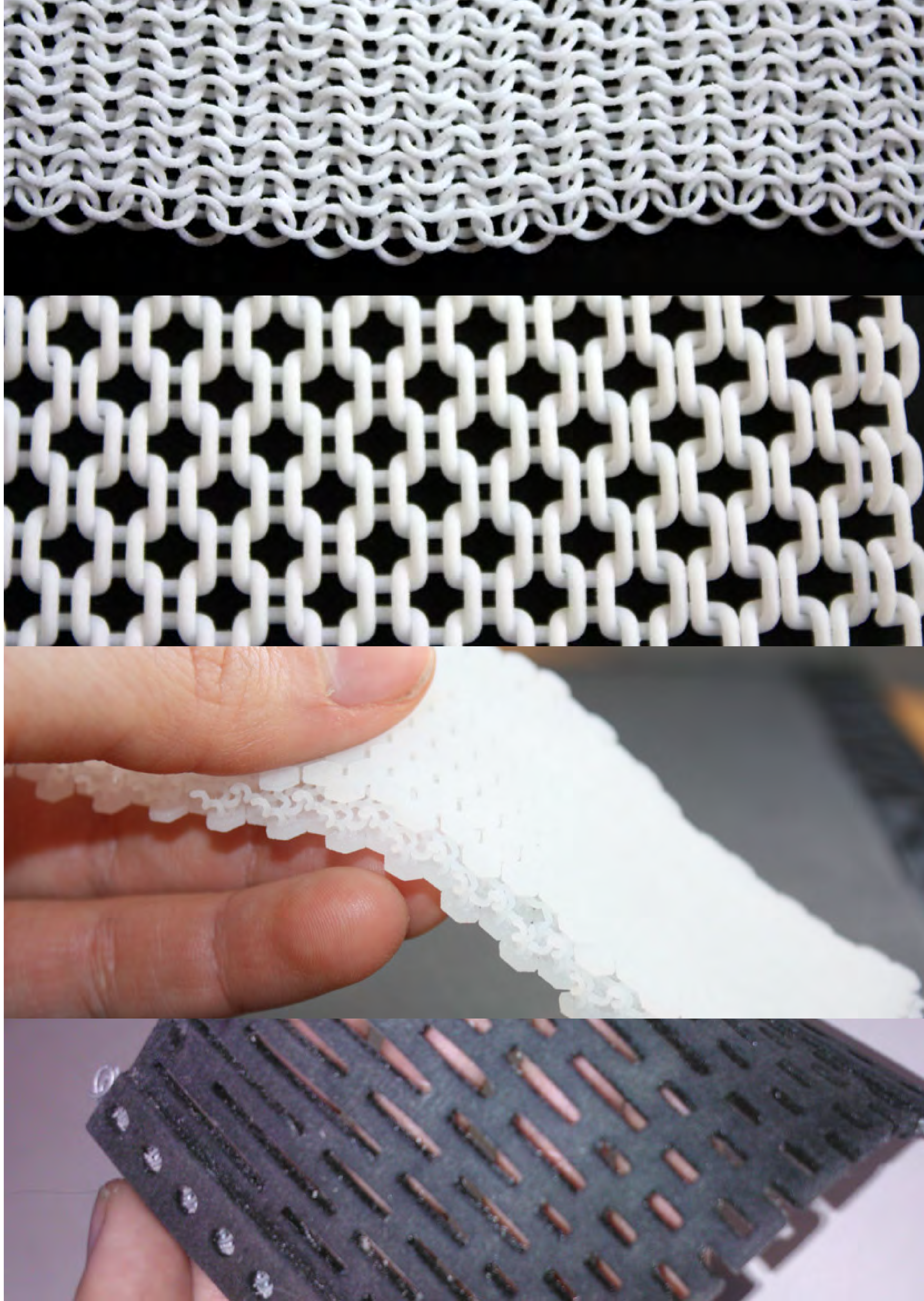
The chainmail-like materials (obviously) resemble chainmail. Although it is a well-known structure in metal, it is not often experienced in daily life. Also, the use of the lighter plastic makes it a completely different experience. The black samples are made of a flexible material, which resembles rubber or natural latex. Only the small chainmail-like material is thought of as textile, none of the others have been described this way.

The interactions with the material are related to movement: throwing, shaking, bending and caressing. The materials invite to be played with, since there is a direct reaction when touched. It was found that the meanings that the samples evoke are *surprising* and *playfulness*.

8.5.3 EMOTIONAL EXPERIENCE

In general, the samples elicit positive surprise, since they are unlike other materials.

The fact that the samples were 3D printed elicits positive emotions. This can be ascribed to the fact that 3D printing is categorized as a 'new' and 'innovative' process, without limitations. This can be used as a positive reinforcement for the materials. On the other hand, this also means that the materials need to be 'interesting', otherwise this clashes with the preexisting image people have of 3D printing.



MATERIAL: NYLON
STRUCTURE: CHAINMAIL
PROCESS: SLS

WALL THICKNESS: 0.6 MM

MATERIAL: NYLON
STRUCTURE: CHAINMAIL
PROCESS: SLS

WALL THICKNESS: 1.4 MM

MATERIAL: ACRYLIC
STRUCTURE: SPRINGS
PROCESS: SLA

THICKNESS: 5.2 MM

MATERIAL: ACRYLIC
STRUCTURE: SHEET
PROCESS: POLYJET

THICKNESS: 3 MM

FIGURE 32. FOUR ANALYSED SAMPLES

8.6 CONCLUSIONS

As a conclusion from this phase, it was found that 3D printed textiles are not a material on its own, but rather a material category, in which a lot of different materials can exist. Combinations of materials and structures can create different materials, which can all have meaning in different application areas. This category is only limited by the technical boundaries of 3D printing, which are at the moment rapidly expanding. Therefore, a material that is found the optimum solution at this moment may be outdated in a matter of months, which should be taken into consideration while designing.

3D printed textiles are a function of material, structure and process (MSP). All three factors need to be taken into account when determining their properties.
From the technical characterization of the MSP, it can be concluded that the material needs flexibility to be applicable to garments. The three strategies that have been distinguished to create flexibility by means of material or structure include multiple assemblies, thin structures and flexible materials. All examples shown in the material benchmark utilize only one of these working principles.

However, when trying to classify traditional textiles, it appears that all three strategies are being used. On an inter-fiber level, the material itself is flexible. Fibers can be thought of as thin structures, because their flexibility is caused by both material and structure. Yarns consist of a large number of intertwined fibers, and can therefore be thought of as multiple assemblies. Knitted textiles consist of only one piece of yarn, which can be seen as a thin structure, while woven textiles consist of multiple threads, making them multiple assemblies. This might imply that the best solution for 3D printed textiles is to incorporate multiple strategies into the material.

From an environmental perspective, the two types of additive manufacturing that have been analysed are currently not better on environmental terms, when compared to traditional textiles. However, since this is a relatively new field, it is safe to assume that there will be improvements in terms of energy-use, efficiency and quality. Additive manufacturing has already some associated sustainable benefits, such as localized manufacturing and little waste during production. Another opportunity that is currently under development is recycling of 3D printed products or waste; the problem of collection could be avoided due to localized manufacturing.

It was found that it is important to be specific about the type of additive manufacturing that is used for the textile, since the results can be very different. Energy consumption is one of the main contributors to the eco-costs, although there is not much data available on this subject. With developments in the field of 3D printing progressing rapidly, it would be beneficial if more research would be attributed to the environmental impact of these processes.

To explore the experiential properties of the MSP, a number of samples was collected, which fit the different categories described above. The samples were shown to different people, and their reactions, remarks and interactions with the MSP were evaluated. It was found that movement and playfulness were important in all the samples, since people were moving the material quite actively, by shaking, throwing and caressing it in their hands. People were also surprised by the feeling of the samples.

The fact that they were 3D printed elicited a positive reaction from people, since this process is still perceived as new, exciting and innovative. Most people could not guess the material it was made of. Sustainable benefits of 3D printing were not found to be relevant.

Although all samples were flexible, only one of the samples was described as a textile. This was due to the small structure of the multiple assemblies, which made it feel softer and more drapable. For most samples, they were not seen as textiles but rather as improvements on plastic components, that were improved in terms of flexibility and breathability of the materials.

9. SOLUTION PRINCIPLES

Over the course of this project, many tests and experiments with the MSP's were performed. The goal was to gain an understanding of the MSP's, the possibilities of current technology and how material, structure and process aspects influenced each other. Samples were collected from all three categories 3D printed textiles, which can be seen as solution principles. In the end, the samples were used to create an overview of what works and what does not.

A number of samples that were obtained and created are presented on the following pages, sorted by means of their classification. More images of the samples can be found in appendix E, in addition with sketches regarding possible structures. Only the samples that showed most promise as 3D printed textiles are shown.

At the moment, there are a limited number of AM processes and materials available. A large part of the process is experimenting and finding the boundaries of the MSP, for which it is important that samples can be created and touched. In addition, it was besides the scope of the assignment to develop a new printing process, which is why materials and processes that were most readily available were mostly used for the tests and experiments. As a result, the structure was one of the most important aspects for experimentation, which is why most of the solution principles are structural solutions.

9.1 MULTIPLE ASSEMBLIES

The category of multiple assemblies falls within structure-based 3D printed textiles. This means their flexibility is entirely based on the structure: they consist of separate parts that are integrated with each other. Nonetheless, this does not mean that multiple assemblies cannot be made of flexible materials, it means they do not necessarily need flexible materials.

Experiments were done with two types of multiple assemblies: chainmail-like structures, consisting of interlocked rings, and hinged structures, consisting of linked panels. The MSP of the hinged structure was not considered a suitable textile, which is why it is not further discussed here.

9.1.1 CHAINMAIL STRUCTURES

Chainmail structures consist of interlocked rings. They can be reminiscent of the metal chainmail armour worn by knights in the middle ages. A lot of different designs can be made using this solution principle, by changing the shape of the rings and the 'weave' pattern. In Figure 33, a number of different chainmail structures are shown with their properties.

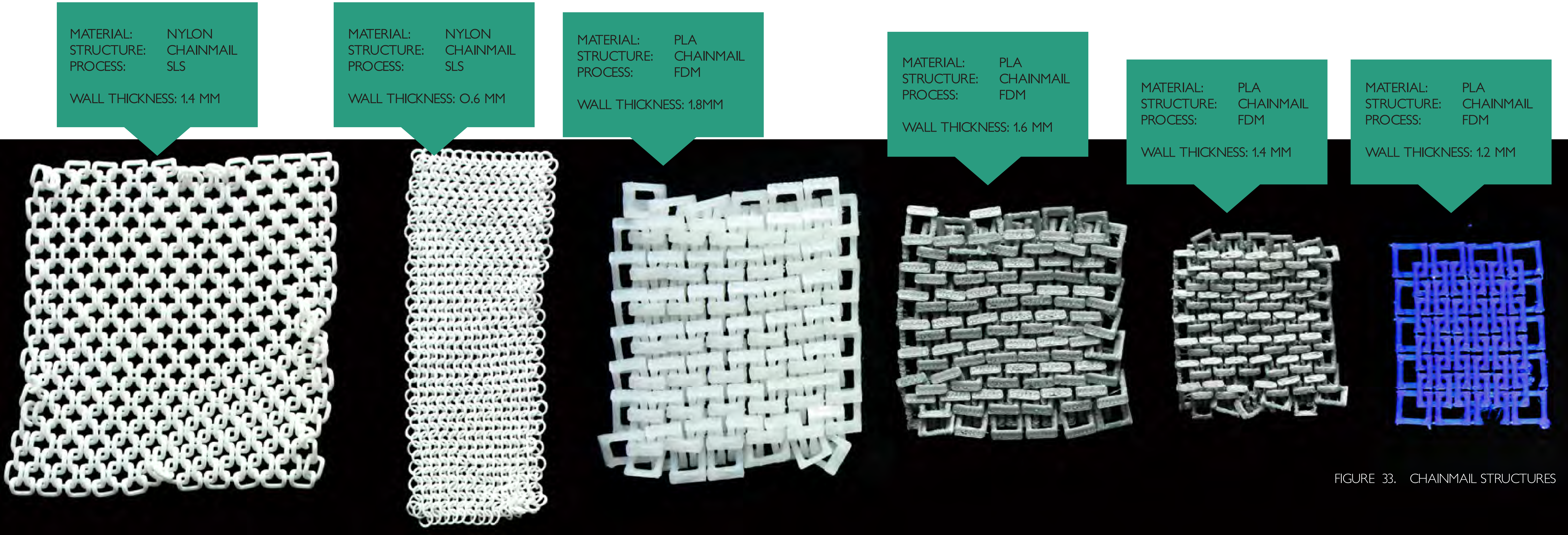
Technical properties

In general, chainmail structures are very flexible and drapable. They are rather strong and durable, since the links are made of solid material. The minimum wall thickness that is possible depends on the used process and material: with SLS a minimum wall thickness of 0.8 mm can be obtained. When material extrusion is used as a production process, the number of possible link designs is limited, since it is harder to create overhanging structures without a support structure. This structure is in general not elastic, unless it is printed in an elastic material.

Experiential properties

Chainmail structures are a little rough and hard to the touch, but the smaller the scale of the link structures, the more textile-like they become.
Chainmail structures can give a relatively high amount of 'coverage', depending on the shape of the links. The colours they can be produced in depend on the used production process and material.

Because of the loose links, the chainmail structures make a rustling sound when moved. The smaller the link



MATERIAL: NYLON
STRUCTURE: CHAINMAIL
PROCESS: SLS

WALL THICKNESS: 1.4 MM

MATERIAL: NYLON
STRUCTURE: CHAINMAIL
PROCESS: SLS

WALL THICKNESS: 0.6 MM

MATERIAL: PLA
STRUCTURE: CHAINMAIL
PROCESS: FDM

WALL THICKNESS: 1.8MM

MATERIAL: PLA
STRUCTURE: CHAINMAIL
PROCESS: FDM

WALL THICKNESS: 1.6 MM

MATERIAL: PLA
STRUCTURE: CHAINMAIL
PROCESS: FDM

WALL THICKNESS: 1.4 MM

MATERIAL: PLA
STRUCTURE: CHAINMAIL
PROCESS: FDM

WALL THICKNESS: 1.2 MM

FIGURE 33. CHAINMAIL STRUCTURES

size, the softer this sound becomes. Although this is not bothering in the samples, it might become a problem when the material is applied to an entire garment.

Design options

There are a lot of options for adjusting the aesthetics and properties of these structures by changing the design. The 'weave' pattern that is used is responsible for the appearance of the material. The shape of the link is also responsible for the appearance, but more importantly it can be used to determine the bending directions of the material, the feeling of the material and the amount of coverage it provides.

Decreasing the size of the links will result in a softer, more textile-like material. However, if the links are smaller than the printing resolution, they will not be able to move freely and stick together. It is sometimes necessary to 'break' the links apart in the material extrusion process.

9.2 FLEXIBLE MATERIALS

Flexible materials fall in the category of material-based 3D printed textiles. Flexible materials can be printed in any structure in order to enhance their flexibility even more. Figure 34 shows experiments that have been done with flexible materials.

Technical properties

The technical properties depend on the type of material. The off-white flexible material is a type of PLA. This material is quite strong and tear-resistant. It is slightly elastic. Drapability depends on the structure it is printed in, when printed as a flat sheet it is quite flexible.

The black flexible material (named TangoBlack) is a type of photo-acrylic. This material is much weaker, it is not tear-resistant and it is easy to break. It is also slightly elastic, but less drapable. These samples were produced at Aalto University, Helsinki. The production of the samples is discussed more elaborately in appendix B.

Experiential properties

The PLA-material has a soft, rubbery feeling, that somewhat resembles paper. The surfaces of the material are matte and a little rough, and show clear line of production, since it was printed in the z-direction. It is semi –transparent, depending on the colour it is printed in. It feels clammy on the skin, in order to make it more breathable a porous structure would be desirable.

TangoBlack is a black, opaque material, although in the shown samples it is combined with a rigid, slightly translucent material. The top surface is very shiny and shows clear lines from the production process, while the bottom surface is more matte. In these samples, an internal structure of a rigid material has been added, which shows best when the sample is bent. Because of the smoothness of the top layer, the material is very sticky when it first comes out of the printer, making it unpleasant to touch. After a while, this stickiness decreases. The surface properties depend on the configuration of the sample in the printer; it can be smooth and shiny, matte or even velvety. This is discussed more thoroughly in appendix B. It resembles rubber, although the response to bending is a little bit delayed, giving it a more 'obedient' feel.

Design options

TangoBlack is an extremely easy material to work with, due to the ease-of-use of the Polyjet printing process. Interesting opportunities provided by this process are the possibilities to create material mixtures in one model. By combining this flexible material with a rigid material in different structures, different properties can be obtained.

The PLA-material is harder to work with, although it is suitable for the material extrusion process, it does not work in all printers. The resolution of the print is somewhat lower than with rigid plastics. By making the material thicker, it becomes less and less flexible.

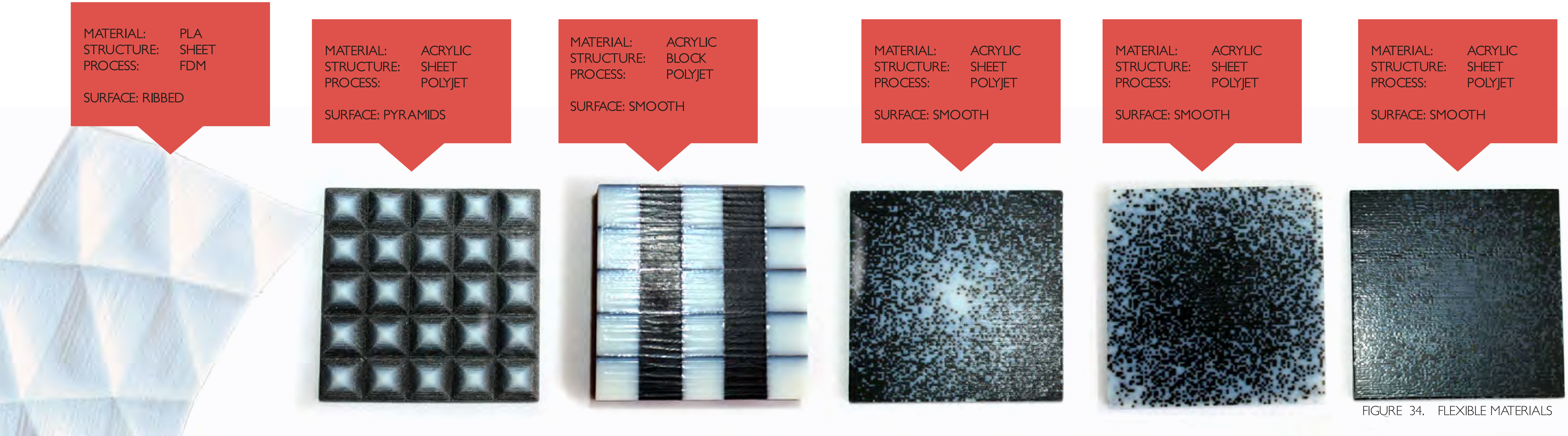


FIGURE 34. FLEXIBLE MATERIALS

9.3 THIN STRUCTURES

Thin structures as a solution principle are a combination of structure- and material-based 3D printed textiles. Due to the fact that the structure is very thin, the flexible properties of the material are utilized. This can for instance be seen in microwave-foils. Figure 35 shows the experiments that have been done with this solution principle.

Technical properties
Due to their thin structures, the materials are generally not very strong. When the structure of a spring is mimicked in the material, they can become very elastic and surprisingly flexible. Different configurations in design can be applied in order to change their properties. In addition, they are lightweight and make efficient use of materials.

Experiential properties
It is surprising to feel this material, since it is unlike other materials. The materials are visually attractive, due to their intricate, repeated patterns. The smaller the wall thickness and the lower the height, the more flexible and soft the material feels. Due to their open structure, the coverage this material provides is low.

Design options
The best results in terms of flexibility can be obtained by creating 'line drawings', with a length-to-width ratio that is as large as possible. The less branched connections, the better, since they break above mentioned ratio. The same is true for the connection points, to many will form a rigid spot in the MSP. When the structure is scaled smaller, the relative wall thickness increases due to the limitations in wall thickness that can be printed. As a result, the material becomes a little less flexible.

9.4 CONCLUSIONS

The experiments shown on the previous pages give insights into the possibilities of 3D printed textiles and the technology.

It was found in general that the smaller the structure, the more the material becomes textile-like. However, this could not be tested for all samples, since they are limited by the boundaries of the AM process.

Although all the materials show flexibility in one way or another, it is hard to think of them as textiles. This makes it even more clear that perhaps 3D printed textiles should be a category of their own, instead of being thought of as regular textiles.

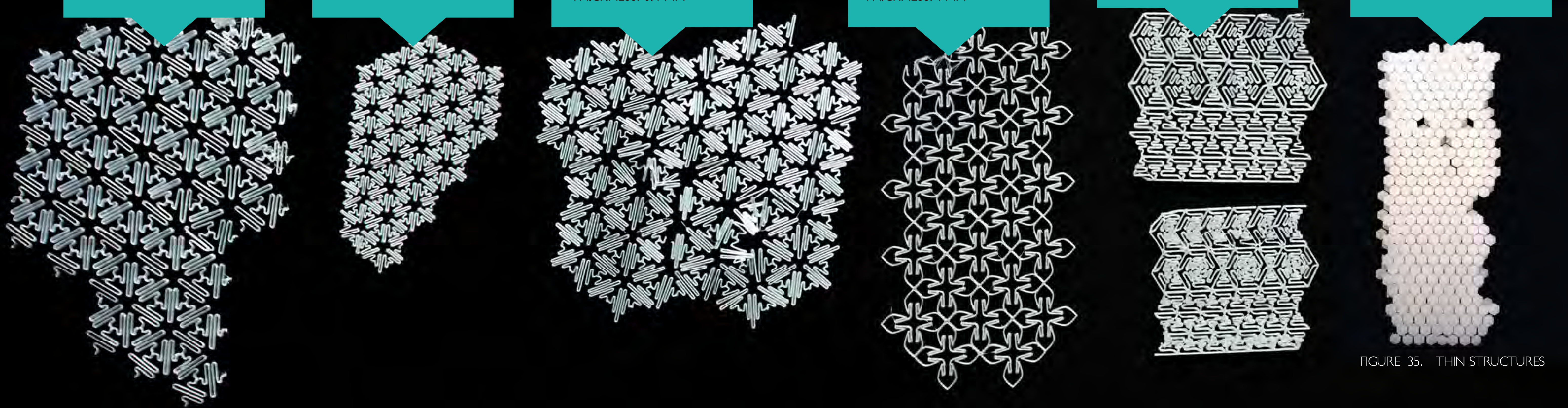
The two solution principles that were found to be most promising were the chainmail structure and the thin structure. The chainmail material is very flexible and drapable, and shows a lot of potential for the creation of different properties by slightly altering the design. However, it is rough and hard to the touch, and the sound it makes when moved could impose a problem when it concerns garments that are worn all day.

The thin structures based on the spring principle show a remarkable flexibility, and are more pleasant to the touch than the other materials. It gives a lot of opportunities for the creation of different aesthetics and properties, by altering the design. The downside of this material is that it is fragile with low tensile strength, which limits its potential application areas in the field of garments.

The experiments can be seen as mapping out the boundaries of the state-of-the-art of 3D printing as a technology. Although there may be alterations of the solution principles possible that have not yet been tried out, the samples are pushing the limitations of current technology in terms of resolution and wall thickness.

Additionally, the limitations in terms of CAD-modelling have also become apparent. For materials such as the thin structures, a line drawing would suffice in terms of a model. However, the software requires a 3D-model as input. This means that the process of creating the designs and transferring them to the printer is lengthy and inefficient.

Another limitation is the amount and type of materials that are available; the options are often limited to rigid or semi-rigid plastics. Although a lot of flexible materials have come to the market recently, they are still not fully developed for easy printing and good results. This may even be an opportunity for the development of AM processes that are specifically designed to print materials with the properties desired for textiles.


MATERIAL: PLA
STRUCTURE: SPRINGS
PROCESS: FDM
THICKNESS: 5 MM

MATERIAL: PLA
STRUCTURE: SPRINGS
PROCESS: FDM
THICKNESS: 1 MM

MATERIAL: PLA
STRUCTURE: SPRINGS
PROCESS: FDM
THICKNESS: 0.4 MM

MATERIAL: PLA
STRUCTURE: SPRINGS
PROCESS: FDM
THICKNESS: 1 MM

MATERIAL: PLA
STRUCTURE: SPRINGS
PROCESS: FDM
THICKNESS: 0.4 MM

MATERIAL: ACRYLIC
STRUCTURE: SPRINGS
PROCESS: SLA
THICKNESS: 5.2 MM

FIGURE 35. THIN STRUCTURES

PART III

MATERIALS EXPERIENCE PATTERNS

Looking at the recent developments in 3D printing, it seems fair to assume that the issues that are now the limits for 3D printed textiles will be solved in the near future. With the fast pace of these developments, it is easy to run the risk of developing something that is too conservative and will be outdated by technology in a matter of months or years. In order to go beyond the technical limitations that exist today and to develeop a new, unique view of what a 3D printed textile could be, a materials experience vision is created. This vision expresses the role of the MSP in an envisioned user experience, as well as the relation it has to the context [Karana et al., in review]. In this case, a more abstract vision was desired, in order to go beyond the intial findings. The next chapters discuss certain factors of the context of 3D printed textiles that were found to be relevant to the project, followed by a statement and metaphor of how the interaction with MSP is envisioned.

10. VISION

In order to construct a vision, the context of 3D printed textiles was explored. An extensive amount of context principles were collected by means of analysing the fields of 3D printing, garments and fashion, and sustainability. The entire list of context principles can be found in appendix F.

During this exploration phase of the context and the material, two themes were identified that played a role in all three fields: personalization and the trend of *slow fashion*. Since these themes had a relevance across all three context fields, they were used as a basis for the statement of the vision. On the next pages, both themes are explained more in-depth.

The current fashion industry is far from being sustainable. From the constant depletion of natural resources, the polluting chemicals that are released into the environment, and the exploited workers in unsafe factories; it is evident that something needs to change.

10.1 SLOW FASHION

In response to the increasingly high pace with which new fashion is being brought to the market nowadays, slow fashion has risen as a new vision for sustainable fashion. Instead of persuading users to buy more clothes than they really need, and using them for a shorter time, slow fashion comprises less obsolescence in a number of ways [Black, 2008]. Slow fashion pleads to make a shift from quantity to quality, to reduce the lasting impact of cheap, products made in bulk that are worn only a few times [Fletcher, 2008]. This movement encompasses the entire life cycle of the product: intelligent material choices for minimal impact and waste; design for long term use and wear; production by means of responsible and ethical trade [Black, 2008; Fletcher, 2008].

By this definition, slow fashion can have an impact on every stage of the life cycle of a product, if the right choices are made. One of the main challenges for slow fashion is to change the mindsets of consumers: the relationship with our clothing will have to change. Constantly pressured by the latest fashion trends, we tend to buy new clothing that we do not need, and we only keep for a small amount of time, until it has been outdated by the latest fashion trends. Delight and desire are the key motivators in the fashion market [Black, 2008]. By increasing the quality of clothing, and by utilizing new technologies to keep them cleaner for longer, it is possible to achieve longer lasting clothing. But in order to change the mindset of users, the aesthetic, functional and emotional value of clothing have to be increased [Black, 2008].

There are a number of ways to increase these values. The aesthetic value can be increased by designing timeless, classic garments, that are not subject to major fashion trends. The functional value can be improved by creating clothing of better quality, or making the garment wearable in multiple ways. Finally, the emotional value can be enhanced by telling the story of the garment, making users more aware, or by allowing personalization [Mugge et al., 2009].

Slow fashion is also related to the maker movement. Reusing old clothes to make something new, knitting a sweater as a present, buying second hand clothes and altering them slightly are all examples of ways in which clothing can be used for a longer time and gain in emotional value.

10.2 PERSONALIZATION

A product can become personal by means of personalization. This can be described as a process in which a person alters the appearance or functionality of the product, in order to increase its personal relevance [Mugge et al., 2009]. This results in a product that is unique and personal to the consumer. During the process of personalization, a consumer invests energy in the product, in the form of time, effort and attention. This energy can be divided into psychic energy, required for the creative choices the consumer needs to make (the type of personalization, design or colours), and physical energy, which is the energy needed to actually perform the personalization [Mugge et al., 2009].

The outcome of the personalization process is a personal product that has a symbolic meaning to the owner. In addition, the product can be used to enforce and maintain the person's identity (self-expressive). Both self-expression and emotional bonding have been shown to increase the degree of attachment to a product, which in turn will increase the time the consumer holds on to it [Mugge et al., 2009].

It should be noted that the effect that personalization can have on the consumer's relation to the product, is not necessarily the same for customization. Customization only increases the choices in product alternatives, which requires lower levels of energy for the consumer as compared to personalization. This means that the emotional bond formed with these products will be lower [Mugge et al., 2009]. Therefore, it is important that the consumer is actively and creatively involved in the personalization process.

The constraints for personalization lay with the consumer; they must have the desire and ability to personalize their products [Mugge et al., 2009]. Restricting factors may be a lack of time, expertise and tools, or a fear of ruining the product [Mugge et al., 2009]. Additionally, a distinction can be made in the manner in which personalization is executed: there is the pro-active way, in which the person has self-directed creative design input, and the reactive way, in which the person relies on support of descriptions, instructions or

patterns [López Pradas, 2014].
This means that it is important to take into account that there should be different levels of customization available to the consumer. Some may want to have a high level of personalization options, while others may think small changes are sufficient.

Three levels of personalization can be distinguished [based on Mikkonen (2013a) and López Pradas, (2014)] and are described with regards to the domain of 3D printed garments:

- Full garment personalization: the product is made to the exact measurements of the consumer (for instance with the help of 3D scanning) and the consumer can choose the aesthetic appearance (colour, touch, details etc.);
- Partial garment personalization: the product is made in standard confection sizes, the consumer can choose the aesthetic appearance;
- Adaptive personalization: the consumer personalizes the product after it has been produced in the manner that is allowed by the product.

10.2.1 PERSONALIZATION VS. (MASS-) CUSTOMIZATION

Although often used interchangeably, there is a difference between the concept of personalization and customization. Customization can be described as the process in which a consumer can choose his preference from a number of predefined choices. These choices are not executed by the consumers themselves, but offered by a company. Examples of this are buying a phone cover, or choosing the features of your car.

Personalization is the process in which a consumer alters the appearance or the functionality of the product, creating a unique and personal product [Mugge et al., 2009]. This can either be done by the consumer themselves after purchasing the product (as executed by the do-it-yourself movement) or can be done by a company, by offering consumers the opportunity to alter or design a large part of the product.

Although customization is part of personalization, the former is often described as system-initiated, while the latter is more often user-initiated [Blom, 2000].

10.3 STATEMENT

A statement was formulated that summarized the experience that should be created for the material and product:

> *"I want people to have an attachment to their 3D Printed garment, by creating a personally engaging experience, like the act of blowing bubbles."*

This statement is derived from findings from the literature and context analysis, remarks from people, and personal experiences. It centers around creating a long-lasting attachment to a garment, which is preferable from a sustainability standpoint as well as from the slow design movement. This can be accomplished by making the garment personal, since people tend to attach more meaning to something that they have personalized [Mugge et al., 2009], and by making the interaction with the product engaging, i.e. preventing that people get bored with the product. It is also an aversion from the meaningless plastic products that are often created by 3D printing, just because it is possible to create them, but without an actual need for them.

'Blowing bubbles' is used as a metaphor for this interaction, illustrating a simple, engaging act that is familiar to everyone. The volatile and delicate nature of the bubbles makes it a challenge to keep them intact as long as possible; or to create the biggest ones. Watching the light react on them is a pleasure; they are inviting to interact with or just to watch.

To help understand what personally engaging entails, and what this means for the properties of the product, this concept is more thoroughly described in the next section.

10.3.1 ENGAGING

The concept of engaging is a complex one, which can have many meanings. The literal definition is to attract and hold interest [Oxford Dictionaries, 2014]. However, in order to translate this to a product or interaction, it is important to know what the attributes of this concept are [O'Brien and Toms, 2008]. There have been many attempts in literature to describe the attributes that engagement relates to, which all place focus on different aspects. However, it can be agreed upon that it is a positive experience, that can be intrinsically enjoyable [Rozendaal, 2007]. This means that the activity itself is the most important part of the experience. It is related to exploring and learning, and the ability to grow and develop in that experience. Therefore, an interaction that provides the potential to grow and realize potential is considered to be engaging [Rozendaal, 2007].

In relation to product design, it is possible to talk about engaging experiences: this means the product should be able to engage the user during use [Chou and Conley, 2009]. An engaging experience can thus be defined as "how people participate and feel in an activity within a specific time and place" [Chou and Conley, 2009, p2]. This implies that important aspects of engaging experiences are feelings, emotions, time and place. Feelings that are experienced by people during engagement are curiosity, interest, confidence and surprise [Rozendaal, 2007], and engaged users are affectively involved, motivated and perceive themselves in control over the interaction [O'Brien and Toms, 2008]. In order to make an experience engaging, two activities are required: an original activity (the function of the product) and a reinforcing activity (an increased interaction) [Chou and Conley, 2009]. For clothing, this means that the original activity is wearing clothing, which should be reinforced by another activity that enhances the experience, in order to make it engaging.

10.4 MEANINGS

From the interaction described by the metaphor, a meaning is chosen that should be expressed by the material. A number of brainstorms were executed in order to break down the interaction to an appropriate meaning. In the end, two meanings were identified as relevant for the material: intriguing and familiar. The two meanings are each other's opposites, however it was found important that they are both represented by the material to a certain extent. They are described shortly below.

10.4.1 INTRIGUING

~ simultaneously arousing wonder and inquisitiveness, a keen and rather pleasurable desire to know fully something to which one's attention has been called ~

This meaning refers to the nature of the material that does not reveal itself immediately, it arouses curiosity to interact with it and it invites to be explored. This is related to movement of the material; only be feeling it and exploring it can the material be understood. In the metaphor of blowing bubbles, this can be described by the elusive nature of the bubbles; without movement/interaction (blowing) the bubbles are just liquid soap. By interacting with it, you fully get to understand the capabilities of the material; the bubbles can be lifted up and blown by the wind. But at the same time, the forces behind the bubbles are mysterious; why do some bubbles pop immediately, and others live longer?

The appearance of the bubbles does not immediately reveal its nature; their surface looks silky smooth, but if you touch them, they pop and reveal their volatile nature. Although we know what to expect, the bubbles keep surprising and attracting our attention.

10.4.2 FAMILIAR

~ well known or easily recognized, a friendly relationship based on frequent association ~

On the other hand, blowing bubbles is a very familiar act. Everybody has done it as a child, and will recognize the feeling of anticipation and joy of being outside on a sunny day while blowing bubbles. Even if we have not done it since we were a child, we will still remember what it was like. We know what will happen if we blow, we know to expect a bubble.

This meaning should also be entailed in the material, mainly because it should be used for clothing. Clothing is a product we wear every day, but we cannot pay attention to our clothing every second of the day; this will become annoying and distract us from our everyday work. With textiles, we have a certain familiarity: we know what it feels like, and even if we like the clothing we wear a lot, it is not necessary to pay attention to it; we can choose not to notice it. Of course, this is only applicable if the clothing is not bothering us, if it is too obtrusive, it will be in our minds all the time. The same goes for bubbles; if you see them float by, you can choose to interact with them, but if you don't they won't be obtrusive.

11. MATERIAL EXPERIENCE PATTERNS

11.1 MEANING DRIVEN MATERIAL SELECTION

An MDMS research was conducted in order to translate the two meanings to formal material properties. The complete findings of this research can be found in appendix G. The most relevant results are discussed in the following section.

The results of the research are clustered in Meanings of Material models (MoM), which depict the meaning of the material in relation to the material, product and user [Karana et al., 2009]; they are shown in Figure 36 and Figure 37.

11.1.1 DESIRED PROPERTIES

Evaluation of the models provided insights into the opportunities and limitations of these meanings for the material. Since they should both be represented in the material, it is important to understand how they can be used to enhance each other, or to limit each other. In some cases, it might be possible for the material to be both familiar and intriguing at the same time, for other aspects it may be necessary to choose for one of the meanings, or even to create an intriguingly familiar material or a familiar intriguing material. This section discusses the results of the models in relation to the desired material.

Interaction

It seems that the interaction between familiar and intriguing materials cannot exist at the same time: it is either an expected interaction, or an unexpected interaction. However, when we think of a material over time, it is clear that the interaction will change; after we have seen and touched an unexpected material innumerable times, we have grown to know it and expect this interaction. On the other hand, when the interaction is as expected, it can never grow to become unexpected without changing. Therefore, the decision was made to lean more towards an intriguing interaction, one that is unexpected and surprising at first, but will reduce over time as we explore the material and learn to understand it, becoming more and more familiar and personal to us.

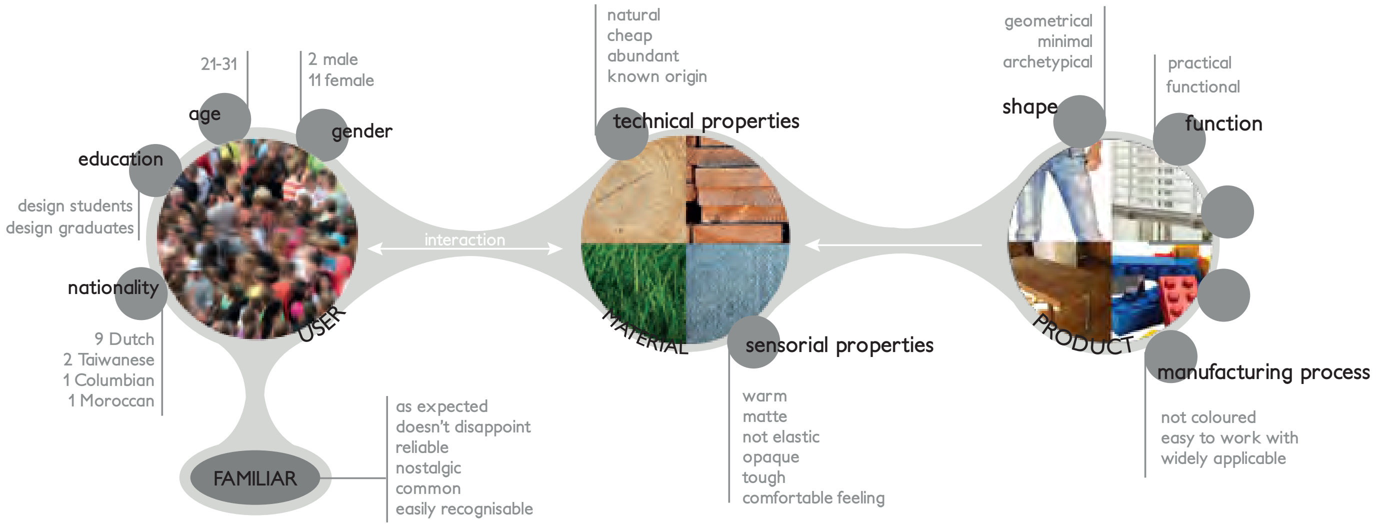


FIGURE 36. MOM-MODEL OF FAMILIAR MATERIALS

To make the interaction intriguing, from the MDMS research it was found that the material should be playful, unexpected, raise curiosity and be inviting to interact with.

Feeling

The feeling of the material was found to be important for both meanings. The feeling must be comfortable, which was found in familiar materials, and also fits well with the product category, since textiles are often worn close to the skin. A comfortable feeling and a pleasurable feeling lay close together, although the word pleasurable also seems to related to playfulness, to some intrinsic value that can be obtained by touching the material.

It was also decided that the feeling of the material should be warm; this is related to familiar materials, but again it makes sense for the given product category.

It would be preferable to use a natural material, since this was found to fit well with both meanings. However, since it is not yet possible to 3D print natural materials, this may be considered more of a future desire.

Performance

The material should be versatile and reliable. Versatility is a value found in intriguing materials, which is related to the different production processes that can be used to shape the material and influence its properties. Although the production process is in this case already determined, 3D printing allows – more than any other production method – the creation of numerous different structures. These structures can influence the properties of the material, just as the production process can. Therefore, the material should be versatile in a way that different structures can be applied to create different desired properties.

Reliability was found in familiar materials. Although it refers to an interaction that is reliable, since the material is well-known, the interaction will be as expected, it can also be expanded to a more performance-based reliability. In this case, the material is reliable for its function and will not disappoint (by failing to perform its function). It can be said that although the material is reliable, this does not mean that it cannot be surprising. Reliability is in that case more a promise that has to be proven over time.

Product

Products for both meanings were found to be functional and practical, but the use of the material should enhance the product, making it more interesting and inviting to use.

The shapes for products with both familiar as intriguing materials can be described as simple, functional and archetypical. This will be kept for the final product, since garments are designed for a large part to fulfil a functionality. It also fits well with the trend of Slow Fashion, described in chapter 10.1, in making a design that is timeless and classic.

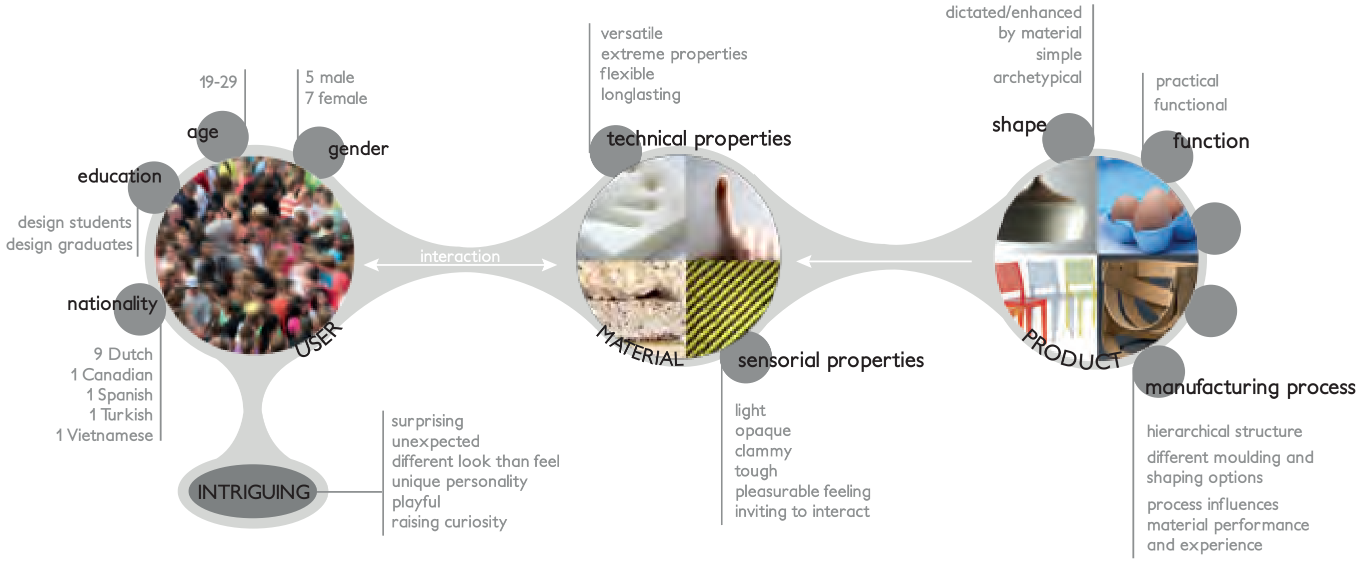


FIGURE 37. MOM-MODEL OF INTRIGUING MATERIALS

11.2 RESEARCH REQUIREMENTS

In addition to the desired MSP properties that were identified from the MDMS research, there are more requirements that are driven by the context of the future MSP. These requirements have been identified in the previous chapters, as a result from literature research, experiments and personal experience.

First of all, the MSP will be a textile-like material, which means it will have to fulfill some of the characteristics of textiles. Most importantly, as has been discussed before, the MSP needs to be flexible. However, the more flexible (or pliable) the MSP is, does not necessarily mean it is a better textile, only that it it suitable for different applications. There is however a minimun amount of flexibility that is required, which is the ability to conform to the body. Next to flexibility, the properties that were decided to be most important (as based on the desirable textile properties discussed in chapter 5.5) are softness to the touch, tear-resistance and absorbence.

Second, obviously the MSP will need to be produced by means of AM. There is not one process preffered over another, since it is the end result that is important. However, part of the consideration was whether there was easy access to the printing process. More importantly, in order to fully utilize the opportunities of AM, the MSP should be suitable to apply property or material gradients to, since this was found to be one of the main competitive advantages of 3D printing.

Finally, sustainability played a role in the choice of MSP. Since there was no insight into the amount of energy per printing process, these requirements focus more on the choice of material and structure. The material should preferably be renewable and recyclable or biodegradable. The combination of material and structure should make efficient use of material, which is defined as the amount of material necessary to produce 1 cm^2 of textile.

11.3 CONCLUSIONS

The findings from the vision and MDMS research that were discussed in this chapter can be used to formulate the desired properties of the material. Two meanings were found to be relevant for the envisioned interaction: intriguing and familiar. Since they should both be represented in the material, it is important to understand how they can be used to enhance and limit each other. In some cases, it might be possible for the material to be both familiar and intriguing at the same time, for other aspects it may be necessary to choose for one of the meanings.

The interaction should be intriguing at first; by exploring and using the material it will become familiar and personal. To make the interaction intriguing, from the MDMS research it was found that the material should be playful, unexpected, raise curiosity and be inviting to interact with.

At the same time, the feeling of the material is important; both for the meanings as for the product category. The feeling of the material should be comfortable, playful and warm, and preferably be recognizable as a natural material.

On a performance level, the material should be versatile and reliable, while on a product level it must be practical and functional, with an archetypical shape.

Asides from the desired properties obtained by means of the MDMS research, there are a number of properties that are dictated by the product category. This has been more thoroughly explored in the previous chapters. Since the material is going to be a textile, it should be flexible and able to conform to the body; it should be non-irritating to the touch; it needs to be tear-resistant in order to withstand forces; and it should have a certain porosity to improve breathability and absorbance. Finally, the material should be produced by 3D printing.

The final MSP requirements are shown in Table 05. They are divided by the the four areas they are related to: requirements related to the vision; textile properties; 3D printing opportunities; and sustainable considerations. Strictly speaking, they should be considered 'wishes', since most of them are not measurable and contain a certain level of subjectivity.

MEANING-RELATED	surprising
	playful
	versatile (in properties)
	inviting to interact
	warm
	natural
	reliable
	comfortable feeling
TEXTILE-RELATED	flexible
	soft to the touch
	tear-resistant
	absorbent/porous
	able to conform to the body
AM-RELATED	3D-printed
	suitable for property-/ material gradients
SUSTAINABILITY-RELATED	renewable
	recyclable/biodegradable
	efficient use of material

TABLE 05. MATERIAL REQUIREMENTS

12. MSP EVALUATION

The MSP requirements identified in the previous section were used to evaluate the three categories of 3D printed textiles, in order to find one to develop further. In order to do so, from each category the most promising samples were used; for multiple assemblies, the chainmail structure; for thin structures the 'spring'-like principle; and for flexible materials the samples created with a combination between flexible and rigid materials. They were evaluated based on the extent to which they fit both meanings (i.e. whether it is intriguing/familiar), to what extent the material could be considered a textile-like material, the opportunities it offers for alterations using 3D printing, and finally for sustainable considerations. Table 06 shows the evaluation of the MSP's with regards to the requirements. The darker coloured cells indicate a better fit to the requirements.

From this evaluation, the thin structure was found to be the best concept material.

	MULTIPLE ASSEMBLIES	THIN STRUCTURES	FLEXIBLE MATERIAL
FIT TO MEANING	• Surprising, playful, inviting to interact • Reliable • Plastic in familiar form • Not versatile • Comfortable to the touch if small enough • Can be irritating to the skin in case of a rough surface	• Raising curiosity • Inviting to interact • Surprising, playful • Pleasurable feeling • Versatile • Not reliable • Plastic in unfamiliar form	• Surprising • Versatile • Not reliable • Not playful or inviting to interact
TEXTILE PROPERTIES	• Flexible and drapable • Tear-resistant • Suitable for application in textile-like applications • Relatively high coverage • Not soft to the touch	• Soft to the touch depending on thickness • Not yet used in textile-like applications • Not tear-resistant • Elastic • Low coverage	• Not soft to the touch • Sticky surface feeling • Not tear-resistant • Non-porous
A.M. POSSIBILITIES	• Different properties by changing link size, link shape and weave design • Not suitable for gradients, more likely a 'patchwork-style	• Very suitable for property gradients • Different properties by changing pattern size, thickness and lay-out	• Very suitable for material and property gradients • Easy, user-friendly printing process
SUSTAINABILITY	• Biodegradable/recyclable • Renewable • Not material efficient.	• Biodegradable/recyclable • Renewable • Material efficient.	• Not recyclable • Not renewable • Material efficient

TABLE 06. EVALUATION OF MSP CATEGORIES

12.1 CONCLUSIONS

Based on the requirements, thin structures was the most promising material to continue with.

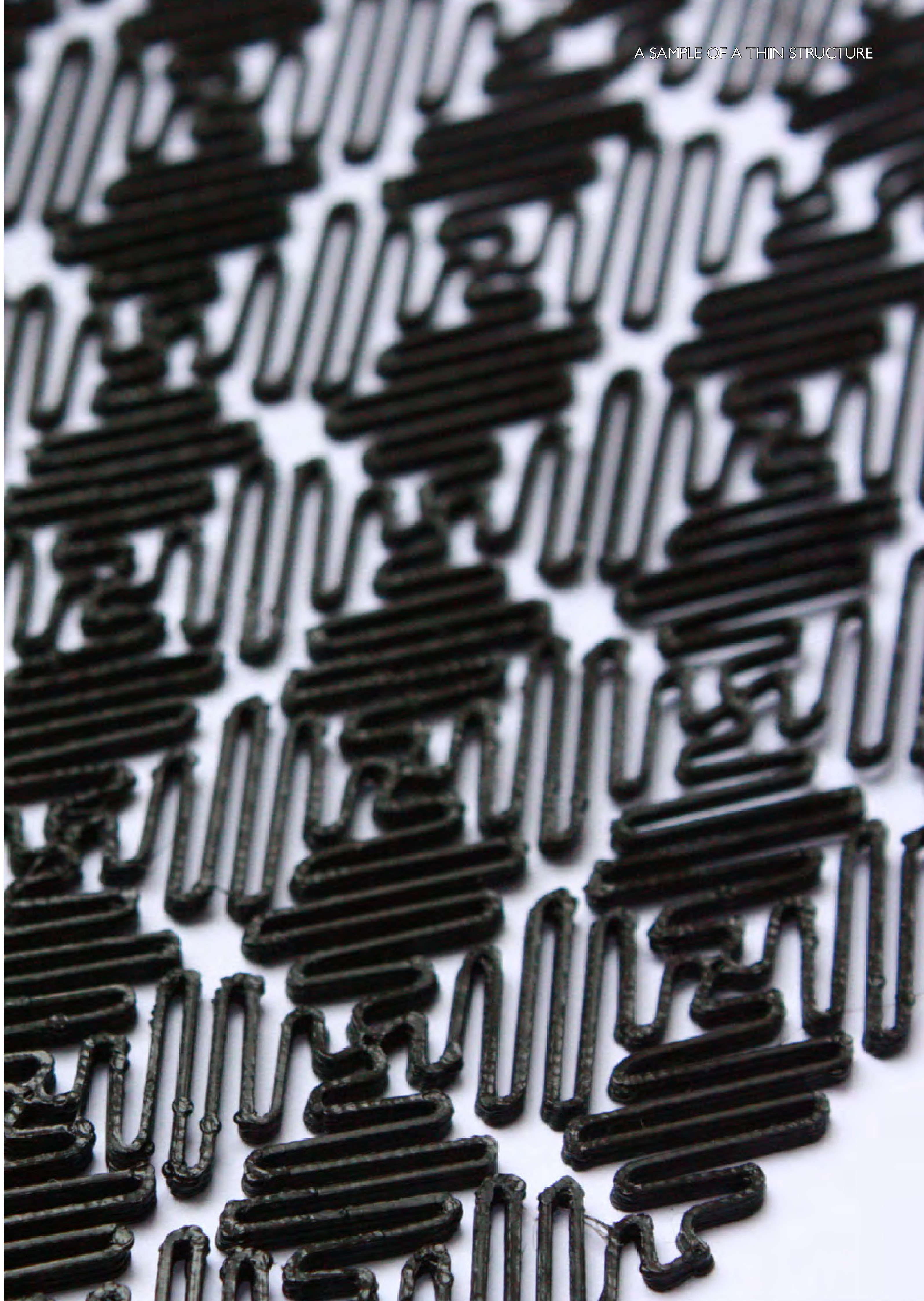
The MSP is found to be more intriguing than familiar. It is intriguing because it raises curiosity, invites to interact, it is surprising and playful, lightweight and has a pleasurable feeling. The MSP can be considered familiar because it is warm, matte and has a comfortable feeling. However, it is not familiar because it is not tough or (prevailingly) opaque and it is not natural (or recognizable as such).

The MSP offers a lot of opportunities for textile-like applications. It is more comfortable to the touch than the other materials, and it is flexible enough to be formed along the body. In its thinnest form, it is not quite as tear-resistant as would be desired.

The MSP is very suitable for the opportunities additive manufacturing offers, since a slight alteration of the design will alter its properties. For example, making the structure larger and thinner results in a softer, more flexible material, while making the material smaller and thicker results in a stronger, firmer material.

The MSP is made of PLA, which is a renewable, biodegradable plastic. The structure makes efficient use of material, since not a lot of material in the z-direction is required to make it suitable as a textile (when compared to the chainmail-like structure for instance, for which a lot more material is required in z-height).

Although it was not a requirement, the fact that this material had not been used for the production of garments before also played a role in the final decision.



A SAMPLE OF A THIIN STRUCTURE

PART IV

MATERIAL & PRODUCT DESIGN

In the previous chapter, an MSP was chosen that was thought to be most promising. This part focuses on the further development of this MSP to improve it based on the requirements, to find a meaningful product application, and finally to design a product with the MSP.

In order to do so, two workshops where conducted: one with fashion design students and one with industrial design students. Although the goals for both workshops were different, in the end the results were used both for improvement of the MSP and for the product design, therefore this part starts with a short overview of the results of both workshops.

Additionally, a number of alterations for the design of the MSP are discussed, which have resulted in the final design of the MSP. A meaningful product application for the MSP has been found and will be elaborated upon, and finally the process of prototyping this product is discussed.

13. WORKSHOPS

13.1 FASHION DESIGN STUDENTS

A workshop 3D printing was given for 13 fashion design students of the KABK (Royal Academy of Art), AMFI (Amsterdam Fashion Institute) and HKU (University of Arts Utrecht) as a means to gain creative input. The goal was to see how fashion designers can apply the possibilities of 3D printing and how they envision the role of 3D printing in fashion in the future. The full report of the workshop can be found in appendix H

13.1.1 RESULTS

The fashion students had some trouble with brainstorming; they explained this is not something they were familiar with from their own education. They also mentioned they were not used to working in groups at all. However, they had some interesting ideas regarding 3D printing and what it could mean for fashion.

- Patterns: the students wanted to include patterns into the 3D printed clothing, for instance by printing different colours at once (more than two).
- Functional aspects: the more functional aspects of 3D printed clothing that were identified were: no need for finishings such as hems; including closures and pockets in the 3D printed clothing; labels/ washing instructions included; no standard sizing anymore; patterns that are continuous across the garment.
- Structures: they were most interested in the possibilities of 3D printing to create organic structures or origami structures, that would be hard to create otherwise.

Some indirect results, that were obtained from observing the participants and talking to them, were the facts that the fashion students were mostly interested in the opportunities of 3D printing to create 3-dimensional parts that they otherwise could not create. This was interesting for them, since they are trained to translate a "feeling" or "image" to a collection of clothing; rather than thinking about the opportunities that 3D printing offers, they were interested in ways they could translate their vision to clothing. This is an interesting observation, since it would seem that the driving force for 3D printed clothing will not (necessarily) come from fashion designers.

Also, their knowledge of 3D modelling was very limited, which means they would need to cooperate with another party that could produce the models for them. Some of the students were used to designing from a material point of view, they would get a material such as plastic bags assigned and would have to create a piece of clothing out of it.

The resulting designs that were sketched or created by the students were not highly innovative and showed influences of the designs they had been shown. However, this could be a consequence of the fact that they are not textile designers themselves, they design the clothing or the vision and chose the fabrics from what already exists and is possible.

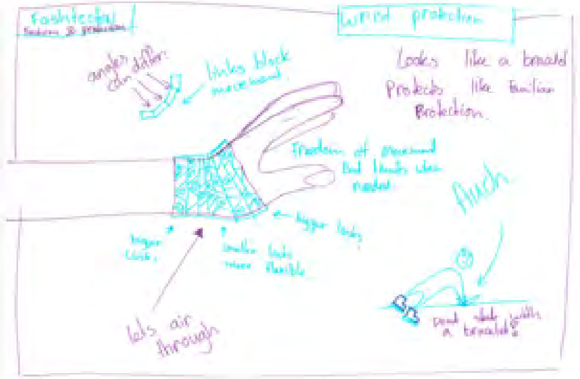


FIGURE 38. DESIGN OF A WRIST PROTECTOR

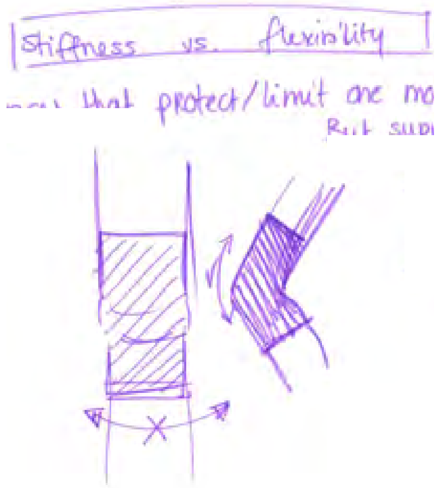


FIGURE 39. DESIGN OF A BRACE

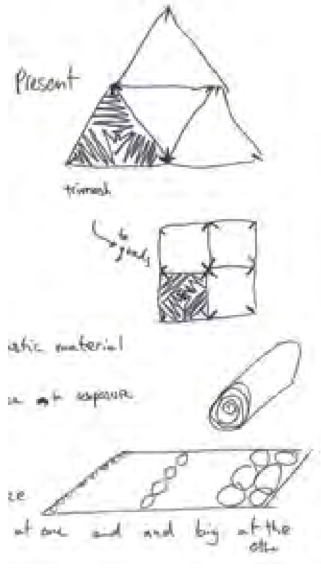


FIGURE 40. DESIGN OF A YOGA MAT

13.2 INDUSTRIAL DESIGN STUDENTS

A workshop Material Driven Design was executed in order to help translating the meanings to materials and products. 12 Industrial Design students were asked to explore one of the 3D printed textiles. The goal of the workshop was to find out how the students evaluated the MSP's based on a given meaning and how they used this to translate into meaningful product design. The full report of the workshop is presented in appendix I.

13.2.1 RESULTS

Both the sensorial/experiential properties of the MSP's were used, as well as the more functional properties, such as flexibility versus stiffness. The students with the chainmail MSP and thin structures used the possibilities of the MSP's to apply local structure changes to adjust the properties. Most of the products they designed were not clothing, but other wearables (however, this may be due to the fact that Industrial Design students are educated to design products, but not clothing). Two groups designed a brace, shown in Figure 38 and Figure 39. The braces utilized the possibilities of the MSP's to be rigid or flexible, so that they could be used to control and limit the movements as a means of protection. Another group designed a yoga mat, shown in Figure 40, which utilized changes in structure to facilitate rolling it up.

From the product designs, it became clear that the chainmail and thin structure MSP's were not really considered textiles, but more as improvement of rigid plastic parts, due to their breathability and flexibility. For the flexible material, the opportunities of AM were not utilized; the product directions they came up with used the MSP to replace other rubber-like materials. It might be possible to conclude from this that the flexible material on its own is not intriguing, but that it would need an intriguing structure to enhance it.

The meanings were not used for both material and product design, but only for the evaluation of the MSP's. Most samples were considered more intriguing than familiar. For this meaning, the function of the products was enhanced by the use of the MSP, although the MSP itself did not dictate the function. Suggestions to make the samples more familiar were to mimic the structure of traditional textiles, or to change the material it is made of to something that is more familiar.

13.3 CONCLUSIONS

The workshop with fashion students gave insight into the manner the fashion designers work, which is mostly interesting from the perspective of implementation of the 3D printed textile.

From the workshop with industrial design students, it was found that the samples did fit the meaning intriguing, but that they were not considered familiar. In order to improve this, some more tests and experiments were done with the MSP, which will be discussed in the next chapter.

14. MSP DEVELOPMENT

14.1 IMPROVING FAMILIARITY

It was found that the MSP fits well to the requirements that were drawn up. There are however, still some improvements that could be made to make it fit better to the vision. Now, the MSP is not really considered familiar. Two suggestions to make it more familiar where derived from the material driven design workshop: the first is changing the material of the MSP, to for instance a more natural material (or more recognizable as such); the second is changing the pattern of the structure to make it more dense (thus covering) and less brittle.

From these suggestions, some more experiments were done to improve the material. They are shown on these pages, and include a flexible material, a wood-filled material, a different structure and two different processes. They are described by their textile properties in the scheme next to them.

However, the material options that have been were thought to be insufficient in making the material more familiar, and at the same time comfortable. The main factor that was identified in this was the fact that it is unfamiliar to have plastic in a recognizable form in a textile (after all, if a polymer is the base material for a textile, it is processed in the shape of fibers, which are not identifiable with more plastics in more common forms).

The flexible PU material made the MSP extremely elastic, which did not help to create a familiar experience, since it became even more unpredicting in behaviour, almost to an annoying level. However, when not in movement, the feeling of this material was softer and warm. This may have been a result of the small particles of powder that were still detectable at the surface.

The acrylic material made the material extremely flexible, and made it adapt to the form of a surface, in a sort of 'obedient' way. However, since it was impossible to remove all the support material without damaging the structure, the feeling of the MSP was cold and clammy, and not comfortable at all.

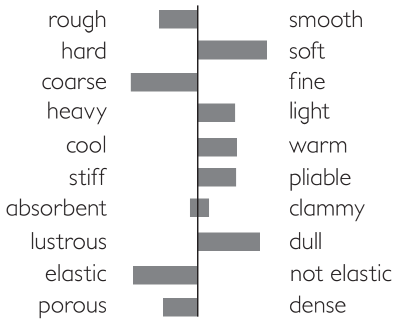
The 'wooden PLA', which is a PLA with up to 30% wood fibers, came close to making the material seem familiar; it has the aesthetic appearance of wood, which from the MoM was found to be the most familiar material. However, the tiny wood particles made the MSP feel more rough, and made it more brittle, which was not desirable.

None of these samples could create the desired feeling for the material: dry, soft, and warm.

Therefore, the main conclusion was that it would be most valuable for this project if a new material could be found that could create a more textile-like experience. In order to do so, some experiments were done to try to improve the (experiential properties of the) material, while still showing potential for 3D printing. It was chosen to base this on one of the most familiar materials in the field of textiles: cellulose, which is discussed more thoroughly in the next section.

MATERIAL: FLEXIBLE PU
STRUCTURE: SPRINGS
PROCESS: SLS

THICKNESS: 1 MM

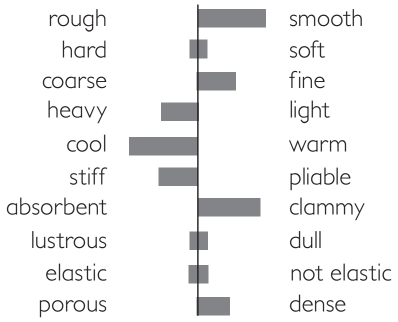


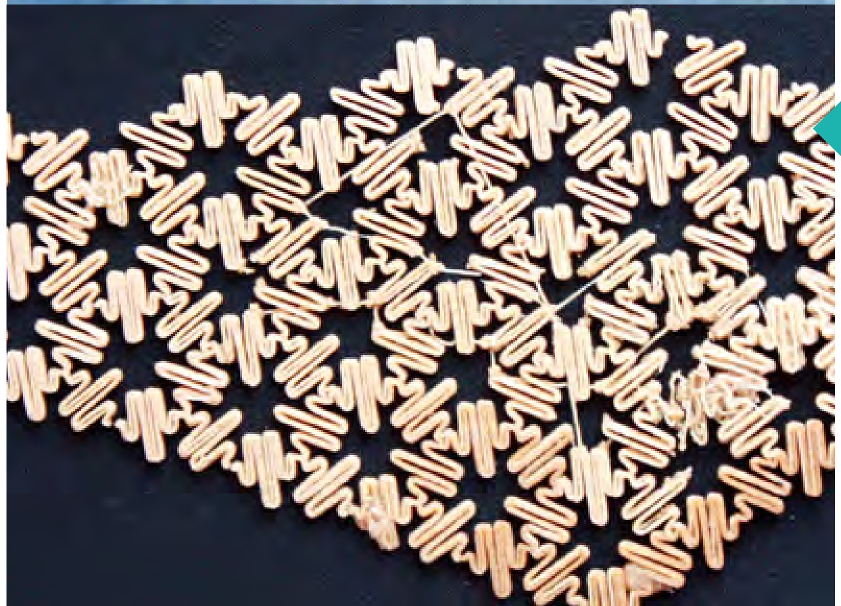
MATERIAL: PLA
STRUCTURE: SPRINGS
PROCESS: FDM

THICKNESS: 1/0.4 MM

MATERIAL: ACRYLIC
STRUCTURE: SPRINGS
PROCESS: POLYJET

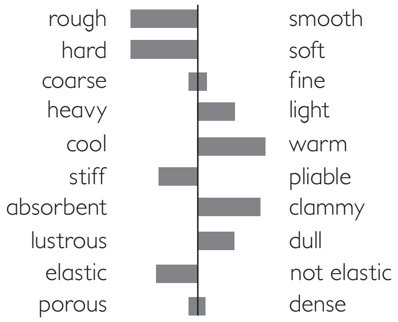
THICKNESS: 0.8-2 MM





MATERIAL: WOODFILLED PLA
STRUCTURE: SPRINGS
PROCESS: FDM

THICKNESS: 1 MM



14.2 CELLULOSE

This section gives an overview of the properties of cellulose, and its potential for 3D printing. This material was researched for several reasons. First of all, cellulose is one of the most common materials used for often used textiles. Second, the properties of cellulose have been regarded as very desirable for textiles. Third, it has been opted that being able to print cellulose would accelerate and increase the possibilities of printing textiles and clothing [J. Mikkonen 2014, pers. comm., 7 April].

14.2.1 CELLULOSE IN TEXTILES

Cellulose is an abundant, renewable material. It can be regenerated from material that would otherwise be waste material, such as cotton linters that are too short to be spun, or recycled wood. It has been found that not the material itself has properties that are desirable for textiles, but rather that the shape and structure of the fiber are responsible for these properties.

In essence, cellulose is nothing more than a polymer, of which the properties depend on the manner in which it is produced. This means it would theoretically be possible to create a filament suitable for material extrusion, however, the results of printing with this material would be similar to printing with other thermoplastics. Therefore, it can be concluded that to recreate the properties of cellulose-based fabrics, it is important to keep the fiber intact and to recreate the hierarchical structure of textiles.

14.2.2 3D PRINTING CELLULOSE

In order to be able to print cellulose fibers as a whole, a suitable printing process needed to be found. Material extrusion was found to be the most suitable process, and also the most readily available process for experimenting. Since cellulose fibers have poor heat properties, it was decided to experiment with cold paste extrusion, similar as used for clays, rather than filament extrusion in which the plastic has to be heated for extrusion.

A number of experiments was conducted in order to find out A) what the potential is of extruding cellulose fibers and B) whether the resulting material would fit the envisioned material experience.

In order to use material extrusion as a production process, it was necessary to mix the cellulose fibers with a binder, in order to extrude them through a syringe or nozzle. The function of the binder is to allow the cellu lose fibers to slide past each other rather than adhere to each other, and to keep the shape intact after extrusion.

A number of different binders were mixed with cellulose fibers in different amounts to create a paste, after which it was attempted to extrude them through syringes with different nozzle diameters.

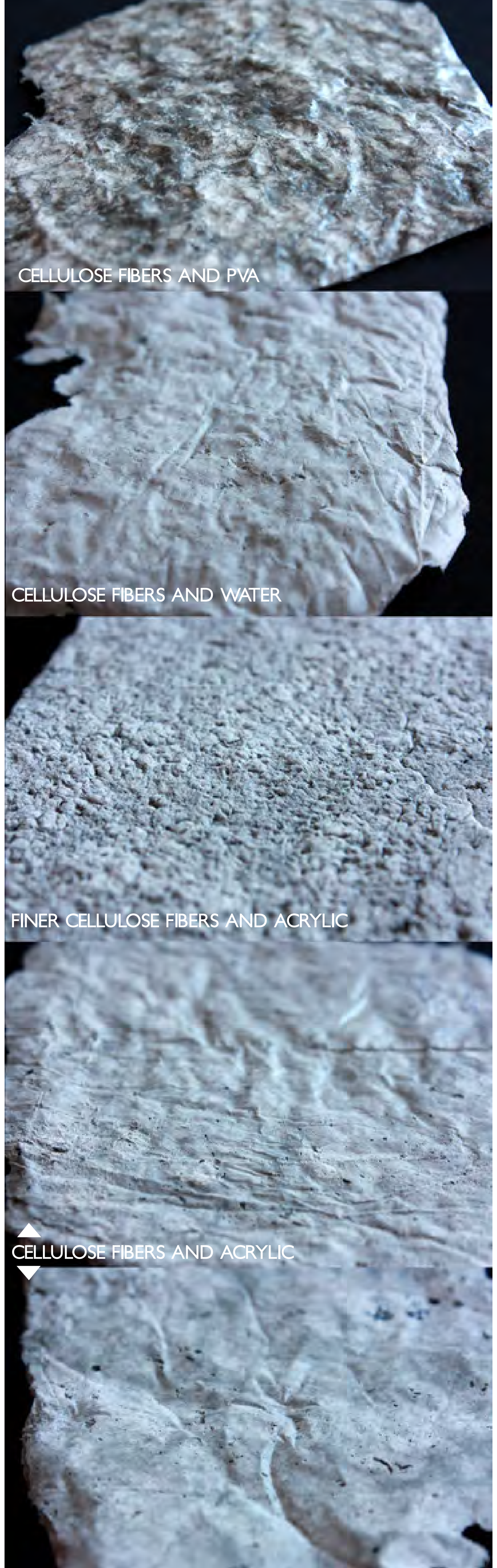


FIGURE 41. MATERIALS CREATED WITH CELLULOSE BLENDS

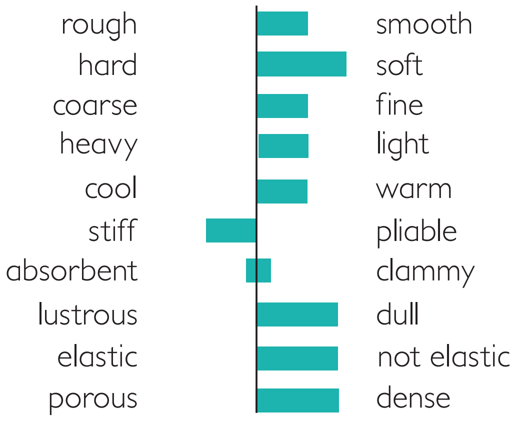


FIGURE 42. PROPERTIES OF CELLULOSE MATERIAL

These experiments are described in more detail in appendix J. Some of the resulting materials are shown in Figure 41.

It was found that a flexible acrylic served as the best binder. It was possible to extrude through a syringe with a nozzle diameter of 2 mm, although at least 30-40% binder (by weight) was necessary to be able to extrude the mixture. The smaller the cellulose fibers, the easier it is to extrude the mixture. When applying pressure, the excess water content is pressed out of the mixture first.

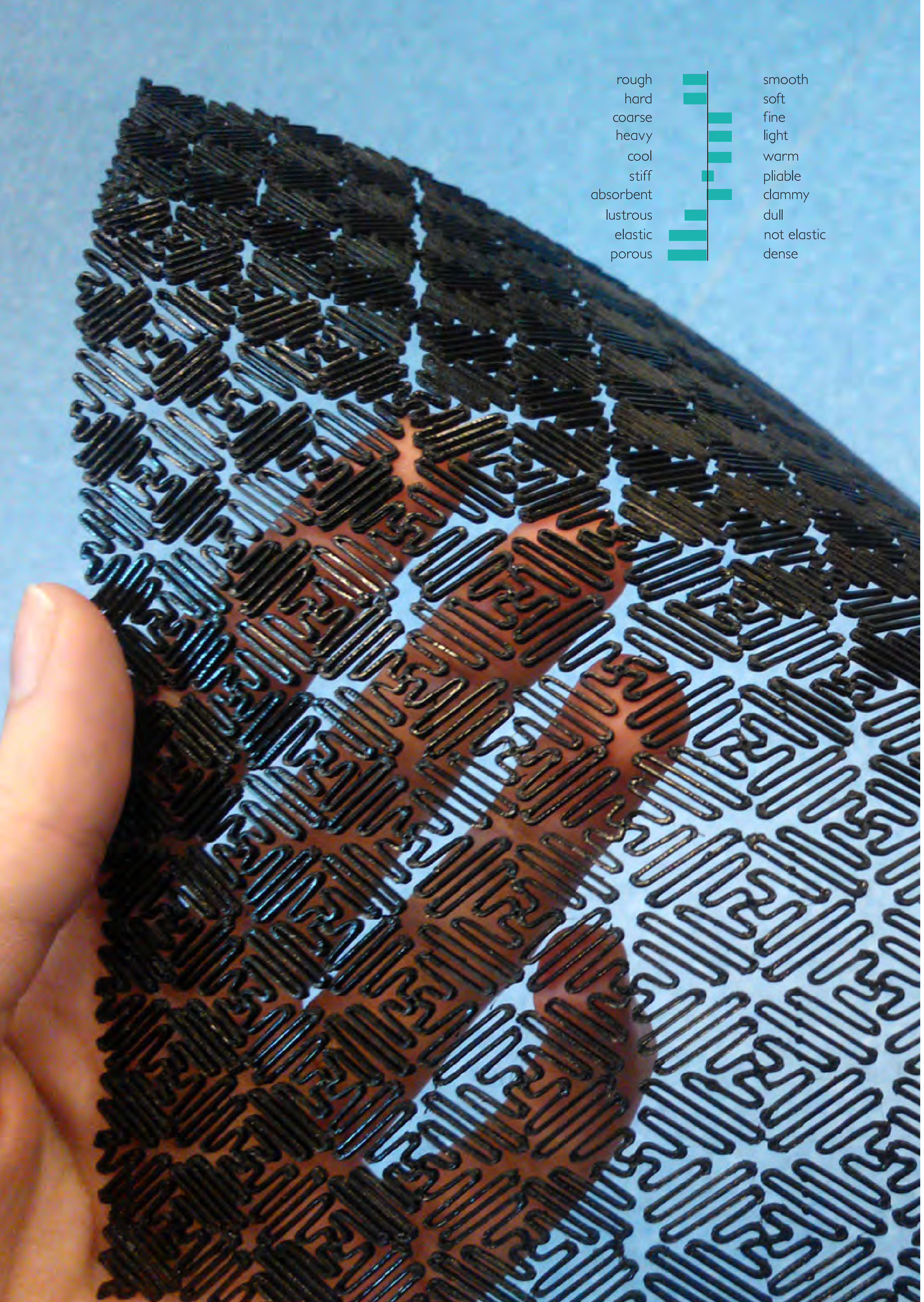
The resulting material is flexible by itself, although this is not strictly necessary due to the structure of the MSP. However, this does give an overall softer feeling to the material, and it is less brittle. It is assessed on the desirable textile properties in Figure 42.

14.2.3 CONCLUSIONS

From the literature review and the experiments, it has become clear that the most promising area for 3D printing cellulose is a process in which the fibers are kept intact. The tests have shown that there is definitely potential for a material extrusion process using a cellulose pulp mixed with a binder, although it could not be successfully printed.

The experiential properties of this material fit the vision well, in that the visible presence of the fibers, in a random pattern, makes the material look more natural and are reminiscent of paper, one of the most common and well-known materials. Also, the process of making the material is the same as making papier-mâché, a common craft process used by children, which makes it a little nostalgic. Finally the feeling of the surface is warm and comfortable, due to the velvety finish, which would make it suitable as a textile. In addition, cellulose has certain sustainable advantages, such as its abundance, biodegradability and the fact that it is renewable. Provided, of course, that the binder is also environmentally friendly.

Of course, these initial tests are not sufficient and should definitely be expanded on, but they do function as a proof of concept. Some recommendations that can be given for future testing include decreasing the size of the fibers even further (for this more professional equipment will be needed), experimenting with different (bio-based) binders, and researching ways in which the drying time can be reduced. Another interesting application would be to see if a suitable binder can be found that can be extracted out of the material, by means of evaporation or another method.



This MSP is adapted from 3D printed Mesostructured Materials by Bastian (2014).

14.3 FINAL MSP CONCEPT: PENTE

As discussed before, the final concept material is a combination of material, structure, and process. The material is envisioned to be, as discussed in section 13.4, a cellulose blend with intact fibers, even though it is not yet suitable to be printed. Since this limited the amount of tests that could be performed with the cellulose blend, PLA was used as the base material for the rest of this thesis. PLA produces good results semi-consistently, although it is not the future envisioned material. Therefore, it should be noted that the properties described below might vary slightly for the actual material concept, since there was no way to test them sufficiently in the time span for this project. The MSP was named Pente.

One of the main reasons this MSP was chosen is because it can be adjusted to create a range of material properties and different aesthetics by applying changes in structure, as summed up below:

- Softness and pliability: can be achieved by a small z-height (<0.4 mm), or adjusting the pattern by increasing the slenderness ratio of each individual 'spring'. In this respect, the individual springs resemble traditional textile fibers. This is illustrated in Figure 43. If printed with the same wall thickness, it means the overall scale of the pattern will be larger.
- Aesthetics: the pattern can be differentiated to change the aesthetics of the MSP. Some examples are shown in Figure 45, such as a hexagonal configuration, a square configuration and a triangular configuration. In this case, an attempt was made to try to make the material as covering as possible, but it could also be interesting to explore more 'open' patterns.
- Rigidity: a larger z-height and smaller slenderness ratio decrease the pliability of the structure, and can therefore be used for more supportive parts.
- Gradients: for all factors mentioned above, it is possible to apply gradients. This means that when the MSP is applied to one product, different properties can be applied to different parts of the product. An example of a size gradient of the pattern is shown in Figure 44.

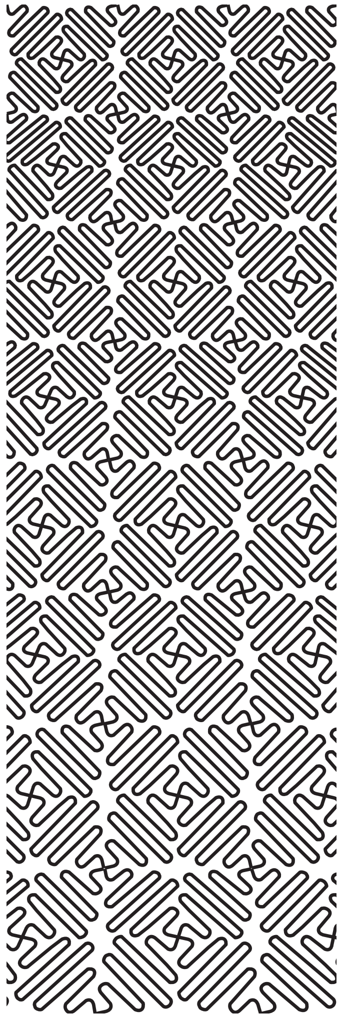


FIGURE 44. PATTERN SIZE GRADIENT

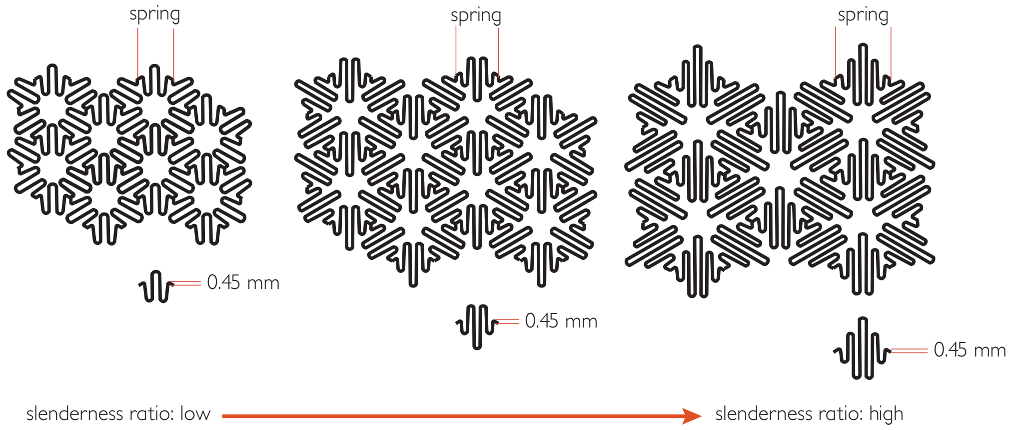


FIGURE 43. SLENDERNESS RATIO OF PATTERN

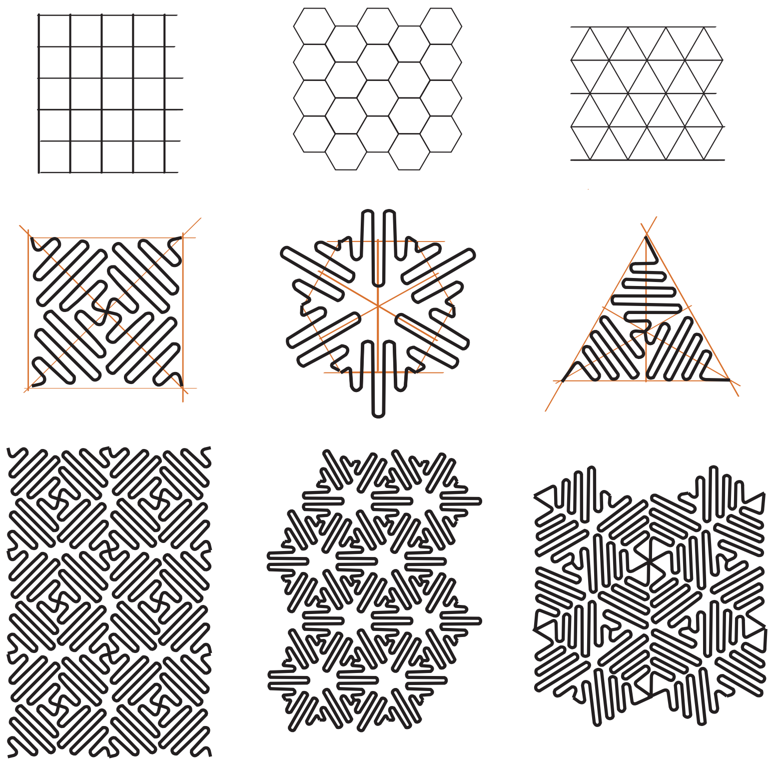


FIGURE 45. DIFFERENT PATTERN CONFIGURATIONS

In addition, applying different materials can also alter the properties of the MSP. The different materials that were used and their effect:

- PLA: currently creates the best combination of flexibility and tear-resistance;
- ABS: more rigid than PLA, and breaks easily;
- PU (SLS): using a flexible material will result in an overall softer feel, but it also makes it more 'elastic' and less structural, such as was shown with a sample printed in flexible PU;
- Acrylic: the acrylic did not maintain its shape very well, making it prone to deformations. Also, although it was still flexible, it lost most of its elasticity.
- Wood-filled PLA: does not improve the overall feel and makes it more fragile, but has an interesting aesthetic.

Different printing processes influence the resolution of the structure and which materials can be used; for instance the SLS process has a minimum wall thickness of 1 mm (for PU), which means the overall structure will become larger, since it needs to be evenly scaled. Two more processes were tried in addition: an SLA process, for which it was not possible to remove the sample from the support in one piece (shown in Figure 46) and Polyjet technology, which had a sufficient result but also a large amount of support that had to be removed, shown in Figure 47.

14.4 CONCLUSIONS

Currently, the best way to produce this MSP is by using PLA as a material and FDM for the process. As a future vision, the material should be a cellulose-bend, but since this is currently not possible to print, the above combination will be used for the remainder of this thesis.

FIGURE 46. SLA SAMPLE

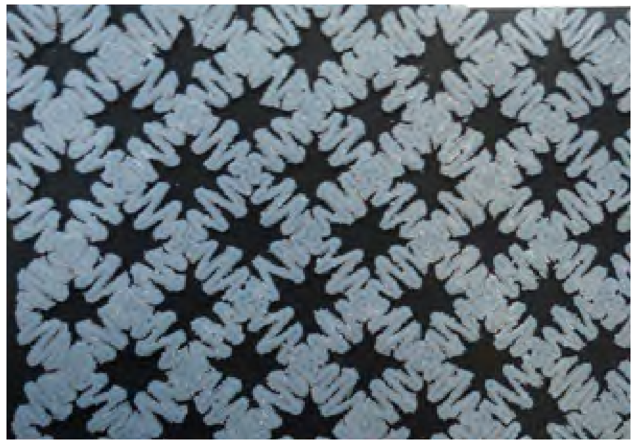


FIGURE 47. POLYJET SAMPLE

15. PRODUCT DESIGN

15.1 MATERIAL EVALUATION FOR PRODUCT CHOICE

In order to find the most suitable product direction that optimally uses the characteristics of the material, first the material is evaluated to find its unique properties. The product should fit in the category garments, as was part of the assignment. Looking at the material, the first noticeable thing is the pattern. Its aesthetic is prevailing. Because of this, the material resembles lace, and can be considered somewhat feminine in appearance. Depending on its exact pattern, it can be a very open material or more covering. As it is very suitable to create alterations in properties (i.e. making the pattern smaller decreases the flexibility of the material), it makes sense to use it for applications where this quality could be used in full, meaning garments that have some kind of support function. By means of a brainstorm session and idea generation, the most valuable product direction was found to be bras.

The final design can therefore be described as the application of a new material and production process to an existing product. Since this gives rise to a lot of room for improvements, first the existing product is analysed more thoroughly in the next section in order to map out these opportunities.

15.2 BRA DESIGN AND REQUIREMENTS

The bra is one of the most close-fitting garments, worn by women all over the world. Although attitudes towards bras may differ from woman to woman, bras have many practical functions, making a significant difference in the lives of many women.

The main function of bras is to provide support to the breasts, intended to improve women's health, posture and ability to participate in sport and exercise. Secondary functions are shaping and protecting the breasts [Zhuo et al, 2011]. Since the bra is such a close-fitting and functional garment, it must adhere to a large number of requirements. It should provide adequate support, shape and lift, fit exactly to the wearer's body, be comfortable to wear and aesthetically pleasing [Hardaker and Fozzard, 1997]. In order to cater to the wide variations that exist in the female body, a large number of sizes and styles needed to be established in order to meet these criteria [Hardaker and Fozzard, 1997].

15.2.1 BRA DESIGN PROCESS

The process of designing a new bra is a lengthy and iterative one. It can globally be divided into three phases [Hardaker and Fozzard, 1997]:

- Concept development: in which the bra is designed, fabric is selected and evaluated and the first pattern is drafted for a sample size;
- Pattern development: in which the sample bra is fitted to a life model, assessed and adjusted as necessary until the style and fit are satisfactory;

- Grading: in which the sample pattern is graded over a range of sizes, which are all fitted to life models and evaluated.

Although these phases are consequently, within each phase many iterations and " fit and amend' loops may take place until the fit and style is perfected [Hardaker and Fozzard, 1997].

Computer-aided design is used for pattern modification and grading [Hardaker and Fozzard, 1997]. The first pattern for a new bra style is drawn by hand, since it depends heavily on the characteristics of the chosen fabrics and the attributes of the style [Hardaker and Fozzard, 1997]. When the first pattern is finished, it can be altered by the CAD-model to adjust for different sizes. Typically a bra will be produced in 20 sizes, however some styles are graded over 56 different sizes [Hardaker and Fozzard, 1997].

The degree of complexity of a bra design is very high; a pattern will consist of a bare minimum of five pieces, but for more complicated models this will increase to 22 separate pieces [Hardaker and Fozzard, 1997]. All pattern pieces will have to be adjusted to grade them for different sizes. Figure 48 shows the components of a typical bra [Chan, Yu and Newton, 2001].

15.2.2 MATERIALS IN BRA DESIGN

In order to perform there function, it is important that the bra fits tightly to the body of the wearer. Therefore, it is important that the materials used for bras are elastic, so that they can form to the body and optimally allow for movement. However, this elasticity of the material often causes uncomfortable pressure points [Zhuo et al, 2011]. This results in impressions of the material on the skin, but can also lead to more serious medical issues. Zhuo et al (2011) showed that the pressure is largest at the hem of the bra, which is caused by the stitching that limits elasticity.

In order to provide for the elastic properties, the fabrics often contain a small percentage elastomeric fiber [Hardaker and Fozzard, 1997]. Asides from elasticity, the fabrics used in bra design should feel comfortable to the wearer, provide easy care and be durable [Liao and Lee, 2009]. It is important for the bra industry to be innovative and keep looking for new, different fabrics, with specific performances, aesthetic qualities and surface textures [Hardaker and Fozzard, 1997]. The fabric properties are the most important factor in determining the shape of the pattern, therefore when a new fabric is applied to an existing style, the pattern has to be drafted again from scratch [Hardaker and Fozzard, 1997].

15.2.3 EFFECTS OF POOR BRA DESIGN

It has been shown that wearing an ill-fitting bra can cause a number of physical and physiological problems, including back aches, headaches, pressure on the nerve system, skin irritations and damage to the lymph nodes [Chan, Yu and Newton, 2001]. An overview of pressure points caused by bras is given in Figure 49 [Chan, Yu and Newton, 2001]. Unfortunately, due to the uniqueness of every woman's body shape and size, the standard sizes produced by bra manufacturers hardly ever fit perfectly. It is estimated that over 70% of women wears a wrong sized bra [Chan, Yu and Newton, 2001]. This can be attributed to the complex sizing system that is used, or to limited knowledge on how a bra should fit exactly. The bra components that are most likely to cause discomfort are (in decreasing order) the underwires, bra cups, shoulder straps, hooks and eyes and the under-band [Chan, Yu and Newton, 2001]. They are discussed shortly below.

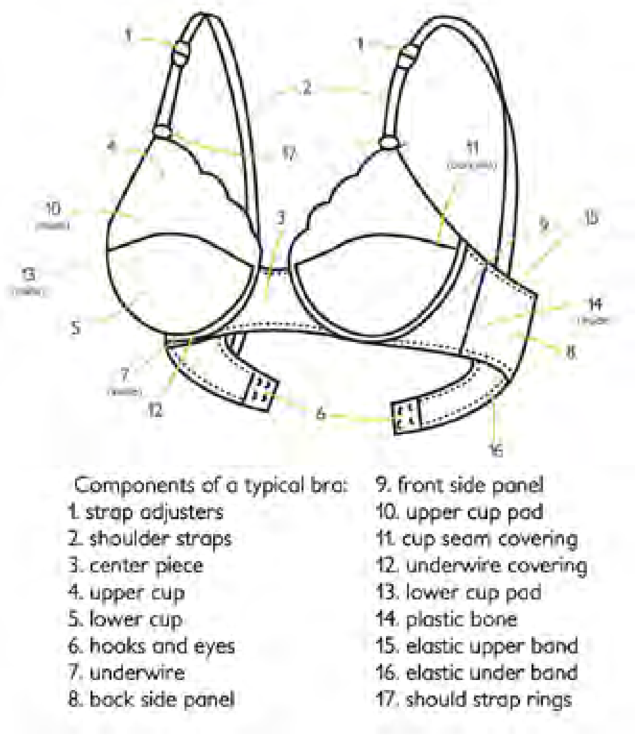
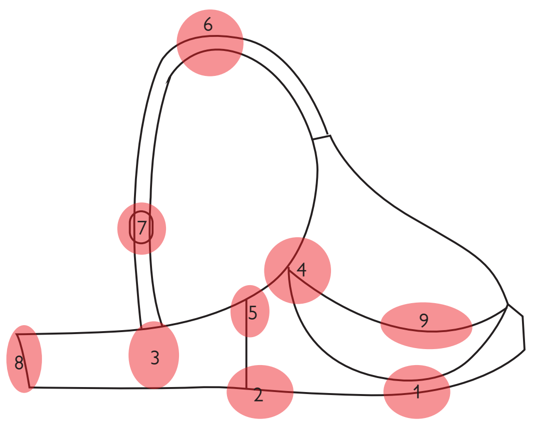


FIGURE 48. COMPONENTS OF A TYPICAL BRA [BASED ON CHAN ET AL. , 2001]



Discomfort caused by bras:

1: under cup/underwire
2: elastic underband and seam
3: elastic upperband and strap connection
4: underwire
5: plastic bone and elastic upper band
6: strap
7: strap adjusters
8: hook and eye closure
9: cup seam

FIGURE 49. PRESSURE POINTS CAUSED BY BRAS [BASED ON CHAN ET AL. , 2001]

Underwires

Underwires are used to provide uplifting support. However, due to their stiffness, this can often cause uncomfortable pressure or poking against the body. These problems are associated with an inappropriate curve diameter and arc length, or caused by the wire damaging and poking through the fabric [Chan, Yu and Newton, 2001].

Bra cups

In order to create a 3-dimensional cup shape, the bra cups usually consist of a number of cut and sewn pieces. This means that there are always seams present in the cup, which can cause irritation on the skin. Additionally, if the shape of the cup does not closely fit the shape of the breast, it will not provide enough support or cause bulging on the sides [Chan, Yu and Newton, 2001].

Shoulder straps

The main function of the shoulder straps is to provide support. If the straps are too loose, they are not supporting enough, and when they are too tight they cause discomfort and can even cause headaches and damage to the skin and nerves [Chan, Yu and Newton, 2001]. If the straps leave marks on the skin, they are too tight. The material of which the straps are made will start to lose elasticity over time. For these reasons, it is important that the bra straps have a slider that allows them to be adjusted to size. Straps should preferably be detachable to offer increased functionality [Liao and Lee, 2009].

Under-band

If the elastic under-band of the bra is too tight, it can cause a number of physical discomforts. Especially for strapless bras, the lifting and support function relies on the under-band, which can easily cause too much stress on the body. Additionally, the rubber strips that are used to keep these bras in place are non-breathable and can result in itching and skin irritation [Chan, Yu and Newton, 2001].

15.2.4 ADVANTAGES OF AM IN BRA DESIGN

The discussion above has shown that bras are indeed extremely complex garments. It is important that bras are close-fitting to the wearer's body, to provide the appropriate support and not cause any physical discomforts. However, their fit is limited by mass-production; since breast shape and size vary per individual, there is no such thing as standard sizes. There are a number of advantages and opportunities that AM can offer for the production of bras:

- Personalized fit; combined with 3D-scanning technologies, AM offers the opportunity to create bras that are produced to exactly fit the body of the wearer, which provide support exactly where needed or desired. This can prevent a number of medical conditions caused by wearing wrong sized bras.
- Integrated production of all parts; the large number of different parts of a typical bra can be reduced and produced in one production step. However, this implies that the material used for 3D printing must be suitable to replace the function of all different materials that would normally be used (more on this is discussed in the next section).
- Incorporation of CAD-systems; since CAD-systems are already used in the bra design process, this could relatively easily be expanded to take over more functions and produce a printable model.
- Shortened production time; incorporation of all parts into one will decrease time for production, in addition the fact that sizing will become redundant for a large part will also decrease the time for development of the design.

These factors show that using AM for the production of bras can have considerable benefits. However, what will (and should) not change is the start of the design process: it is still important that the (initial) pattern is drafted carefully and full attention is paid to the fit and comfort of the style. Expertise is still necessary in order to ensure quality. CAD models can play a larger role in the design process, by fitting the initial pattern to the unique size of the user.

15.3 FINAL PRODUCT DESIGN: ARALIA

The final product design is a corselet, which is essentially a bra with part of a shirt attached to it. It is shown in Figure 50. It is named Aralia; the first part of the name refers to the family of ivy, a plant that can grow unto buildings and adapts to their shape.

The choice was made to design a corselet instead of a bra in order to utilize and demonstrate the soft, supple qualities the material can have, which are not suitable for the supportive parts required for bras. It is also more versatile as a corselet, by making small adaptations the product can for instance be turned into a T-shirt. In appendix K, some sketches from the design process can be found.

The entire product is 3D printed exactly to the size of the user. More on the production is described in section 15.4. Since it is custom-made, this means that in theory the exact design can differ, depending on the needs and desires of the user. The design as presented here can be seen as a basis for further adjustments.

15.3.1 EXPLANATION OF THE DESIGN

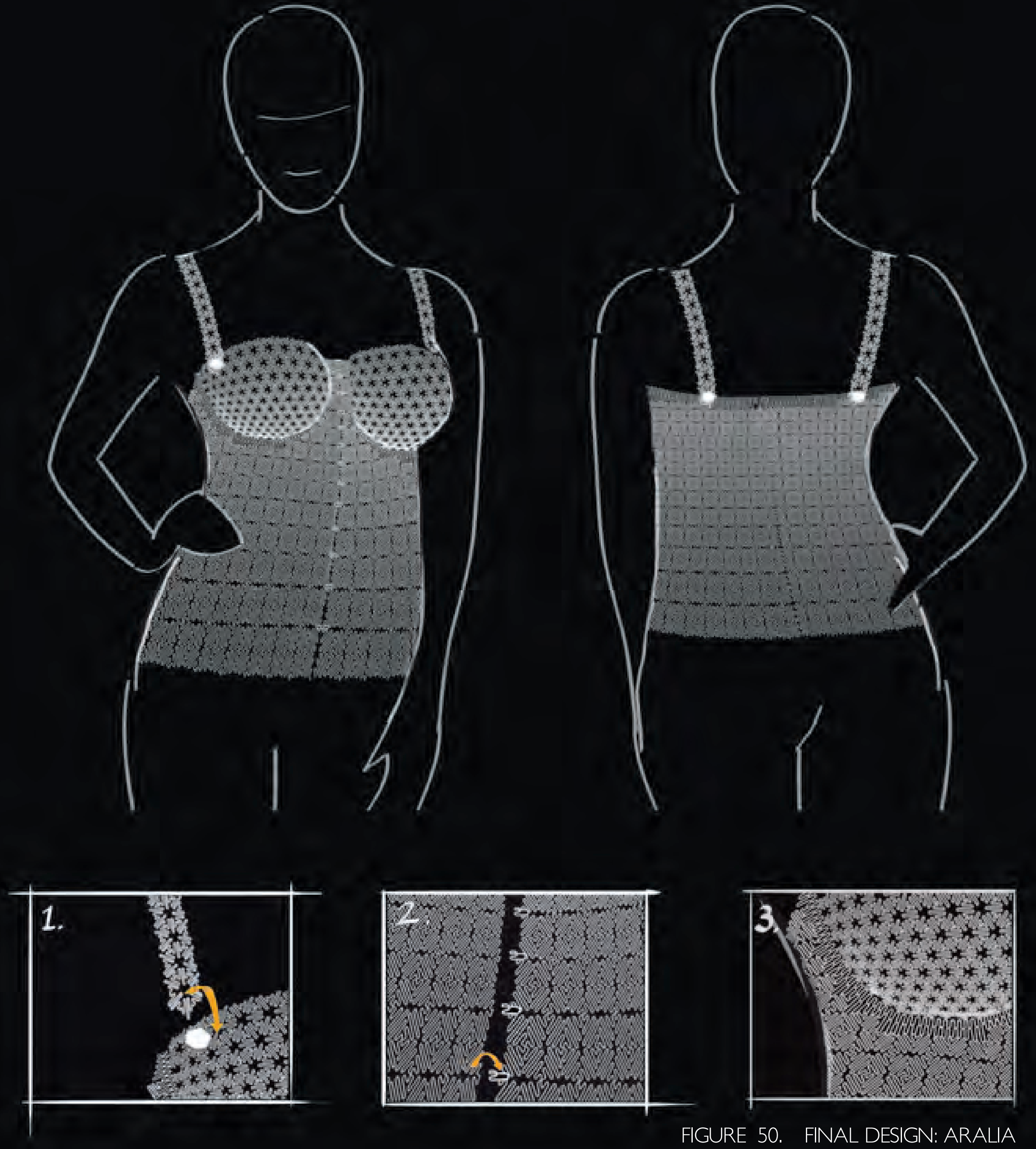


FIGURE 50. FINAL DESIGN: ARALIA

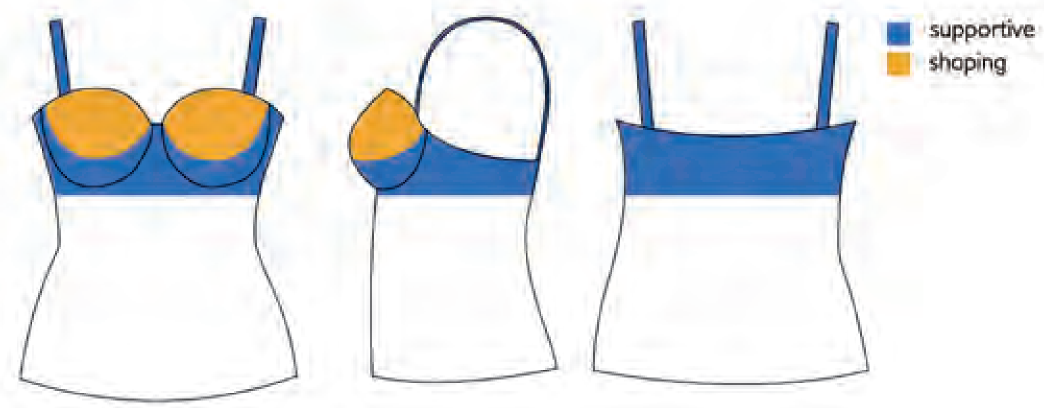


FIGURE 51. SUPPORTIVE AND SHAPING PARTS OF THE PRODUCT

The final design of the Aralia is shown and explained in Figure 50. Two types of the pattern of the material are used: the hexagonal configuration for the cups, in order to accommodate the round shape, and the square configuration for the other parts. In order to provide for the supportive parts, gradients are applied to the material: a gradient in size and a gradient in thickness. Supportive, more structural parts have a smaller pattern size and are thicker (up to 1.5 mm), while the parts that do not have to provide support are thinner (~0.6 mm) and have a larger pattern size, which makes them softer and more pliant. Figure 51 shows the supportive and shaping parts of the garment. It should be noted that applying the gradient in pattern size results in a tapered cylinder effect, which means that this can be used to compensate for natural curves of the body.

Cups

The hexagonal configuration is used for the cups. In order to provide support, a gradient is applied on the cup that is more structural and thick on the bottom part, which decreases towards the top. The amount of support can be adjusted to individual preferences and desired functionality, for instance for a push-up effect it is suggested to have a thicker bottom part that only slightly reduces towards the top. The cups have no seams that could be irritating on the skin.
The underwires that are traditionally used for support are replaced by gradients in material. This prevents localized discomfort caused by underwires that dig into the skin, by creating a larger area for pressure distribution.

Straps

The length of the straps cannot be adapted after production, as is currently common for bras. In this case it is assumed that this feature is unnecessary, first of all since the straps are produced at a custom length optimised for the user, second of all since most women do not change the length of the straps regularly, and third of all since the sliders are a common cause for discomfort. Testing should confirm whether or not this would be necessary, for instance if the elastic would stretch out over the course of time. The straps are detachable, as is preferred by women and it makes the design more versatile, since it can also be worn strapless if desired. The straps are attached to the side of the cups with a button closure, which was found to be the best way to keep the closure as flat as possible. The button closure is illustrated in Figure 50(1).

Closure

The corselet has a front closure that runs along the length of the product, which makes it easier to put on. Even though the material is elastic, having to pull it over the head to put on may damage and break the connections of the material. Also, not unimportantly, hair gets stuck very easily in the open stretchable structure. The closure uses hooks, these are used frequently in underwear design and can utilize the rounded openings that the material naturally has. This is demonstrated in Figure 50(2). Only hooks are used (instead of hooks and eyes), pointing outwards, which means there is no chance of the hooks pressing in the skin.

Edge

Due to the square pattern of the MSP, it was not possible to create a smooth edge. Therefore, the choice was made to add an edge to the top side of the material, in order to make it look more finished. The edge was designed in such a way that it would be as elastic and flexible as the rest of the material, and that it would be able to compensate for the 'stepped' edge of the pattern. In addition, this edge could be used to accommodate the

15.4 PRODUCTION

The entire product will be produced by means of material extrusion printing (see chapter 4.2 for an explanation). However, in order to print it most efficiently and exactly to size, a more futuristic process is envisioned. The process is visualized in Figure 52. First the sequence of production is described, after which the technological feasibility of this scenario is discussed.

15.4.1 PROCESS SEQUENCE

First, a 3D-model of the user is obtained by 3D-scanning the torso. This will allow it to be produced exactly to size. This model is then imported into software, which can map the structure of the material to the model in order to create a preview of the product. At this point, adjustments can be made to the structure of the material, by for instance creating more or less structural parts, changing the length etc.

The model is transferred to the printer. First a quick model of the torso is printed on a 1:1 scale, in a recyclable material. The corselet is printed directly onto this torso, which means the printer is able to print on freeform surfaces. When the model is finished, it can be taken out of the printer, after which the torso can be recycled.

15.4.2 TECHNOLOGICAL IMPLICATIONS

The optimal production process for the product requires a different manner of 3D printing. The product should be printed all in one, eliminating the need for assembly and preventing lines and seams from occurring. The printing process requires printing on a freeform surface, of which a proof of concept has been shown in a graduation project by Fortuin (2012), although still a lot of development is necessary before this can be implemented. Also, the development of freeform 3D printing by means of 3D printing pens (such as www.the3doodler.com) and a metal 3D printing robot (www.jorislaarman.com) show that it is technologically possible.

Other additions that will be required for the printing process are the possibility of printing with multiple materials (a recyclable plastic for the dress form, a cellulose mixture for the garment), which should preferably only require one 'arm', and the presence of two 'build platforms': one for the dress form, the other to mount the dress form on in order to rotate.

3D-scanning is an existing technology that is becoming more popular with the rise of 3D printing. There are a number of companies from which it is possible to order a miniature version of one's self produced by 3D printing. In addition, some companies are combining 3D-scanning with the production of custom garments (such as www.3d-a-porter.com).

Special software would need to be developed in order to fulfil the following tasks:

- Project the pattern on the surface of a freeform object
- Creating structural and less structural parts (in the form of size-gradients)
- Applying 'lifts' or shape corrections where necessary

In addition, it would be valuable if the process from model to print would be simplified: since the 3D model can in essence be considered a line drawing in the form of a freeform sheet, it would be more efficient if the printer could be driven by the lines itself, without requiring this to be sliced in horizontal layers. Successful testing of this principle has already been done by Fortuin (2012).

15.5 USAGE

The Aralia aims to improve the fit of existing bras and corselets, by offering a custom-made design. The integration of support within the design itself reduces localize pressure, by creating a more even pressure distribution. Compared to regular bras, points of discomfort as shown in figure Figure 49 that have been eliminated are the strap adjusters (7), the underwire (1), cup seam (9), the hook and eye closure (8) and the plastic bone (5). Since there is no need for seams, the elasticity of the material remains even across the design, eliminating irritations caused by the elastic upper and under band (2 & 3). Additionally, since the product is made to measure, discomforts caused by wrong sizing will also be eliminated.

The product offers a number of options for customization: the amount of support (a function of material thickness and structure size), the placement of the support (e.g. the product can be turned into a correcting top by adding more support in the bodice part), the nature of the cups (½ cups, ¾ cups or full cups), the length of the bodice and the colour of the material.

As the product is a type of undergarment, it is meant to be worn under the clothes due to the open structure of the material. Therefore it is most important that the product is comfortable to the skin, which is also tested with the prototype.

Some tests were performed to see whether the product would be machine washable. Both a PLA sample and a sample of the cellulose blend have been washed in a washing machine at 30 degrees. The PLA sample came out disfigured and torn, as is shown in Figure 53. The cellulose sample did not withstand the washing machine at all, as shown in Figure 54. Therefore, in order to not ruin the garment, it would be advisable to clean it with a little water and soap.

15.6 IMPLEMENTATION

A complete business model falls outside the scope of this assignment, nevertheless some suggestions can be made for the market and implementation. The product will be sold in specialized lingerie stores, at first as an addition to the normal collection. The store would have to invest in specialized equipment, namely a (3D-) scanner (or other means of producing a 3D-model of a body), modelling software and a 3D printer. It would be recommended to start with a small selection of possible designs, which can be expanded over time. Also, a showroom with some premade products would be suggested.

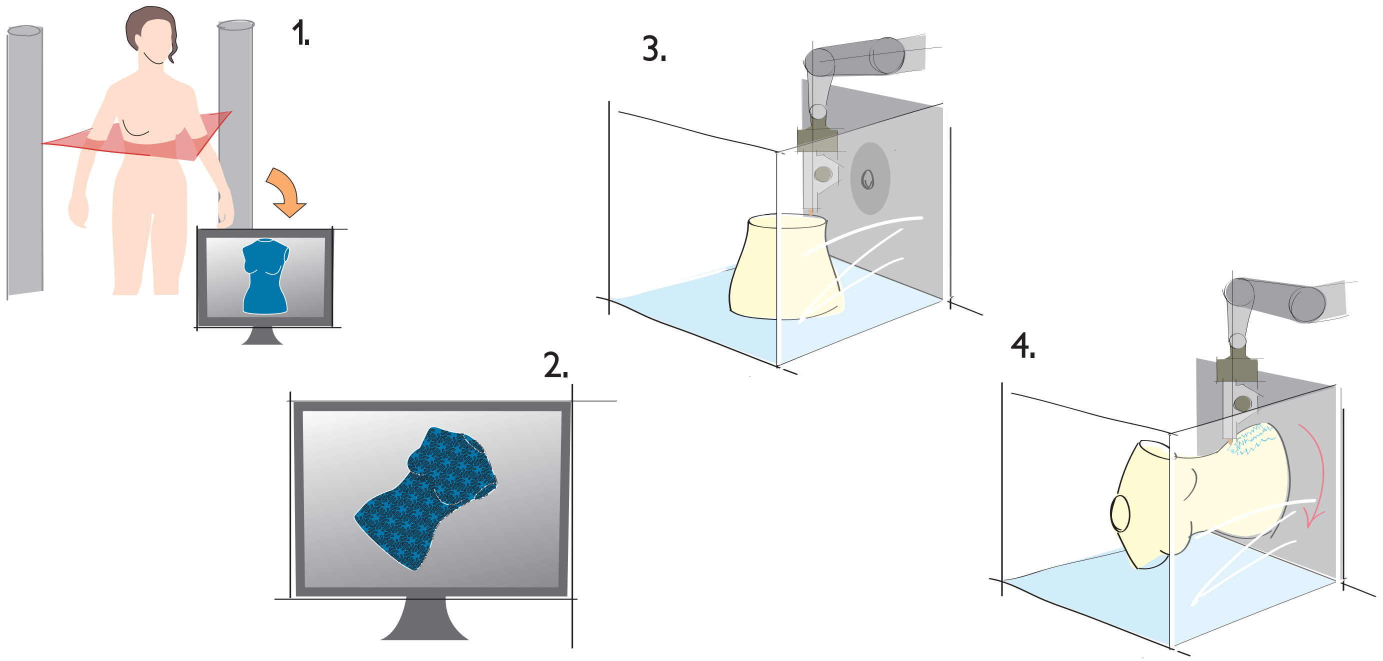
The staff of the store should be specialized or trained, in order for them to give advice and to create a design (in combination with the software) that adheres to the wishes of the client.

Although the bust should be made from a recyclable material, it would also be an option for the clients to have their bust produced once, after which they can keep it. In this case, they would have to bring it in again in order to produce a new product. A deposit system could be set in place for this scenario, to ensure the store will get the bust back for recycling.

The product itself can be returned to the store when the customer is finished with the product. The customer can (partly) exchange this for a new product. In store recycling options should be present, so that the material can be used for a new product on location.

FIGURE 53. PLA SAMPLE BEFORE (L) AND AFTER (R) WASHING MACHINE

FIGURE 54. CELLULOSE SAMPLE BEFORE (L) AND AFTER (R) WASHING MACHINE



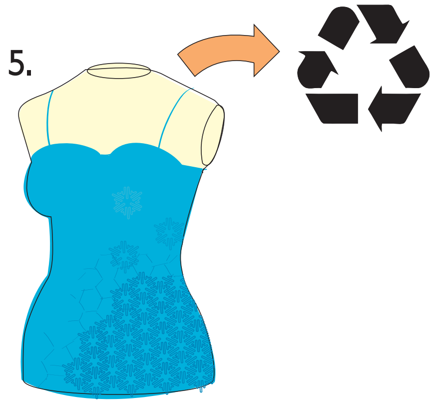


FIGURE 52. FUTURE PRODUCTION PROCESS

15.7 LIFE CYCLE ANALYSIS

The goal of this LCA is to provide a comparison with the LCA that was performed earlier in this report, as well as to provide a comparison with the environmental impact of traditional textiles. This LCA will differ from the last in that a different process, material and scenario are used.

15.7.1 SCENARIO 3

The functional unit is again 1 kg of 3D printed textile. One scenario is analysed: the product is made from PLA by means of fused deposition modelling (FDM). The choice was made to only analyse PLA as a material, since the envisioned cellulose blend is not fully developed, which means the resulting findings would not necessarily be true. However, it can be said that cellulose is an abundant, renewable and biodegradable material, which will have a positive influence on the environmental impact. Therefore, the choice of binder(s) will determine whether the material will score better or worse than PLA. Other than that, the scenario is the same as described in chapter 15.6 regarding the implementation. It is shown in Figure 55.

The PLA is shipped from China to the Netherlands, after which they are shipped to the store locations. The product is produced in a store in the city center, after which it is taken home with the user. Since PLA is not machine-washable, it should be cleaned with a little water and soap. At the end of its life, the product can be returned to the store (in case of PLA) where it is recycled.

15.7.2 ASSUMPTIONS

The following assumptions are made:

- No waste results from the FDM process;
- Transport of filament from China to the Netherlands is 10,000 km by boat;
- Transport within the Netherlands is 75 km by truck (see appendix D for an explanation);
- Material for the dress form is recycled instantly (within the system, as shown in Figure 55, therefore the necessary material is left out of this LCA, however the costs of energy have to be included;
- The influence of the use phase is smaller than 1% and thus negligible;
- Transport distance of the product is 10 km (one way) by car
- Recycling of the product occurs in half of the cases, 100% of this material can be recycled

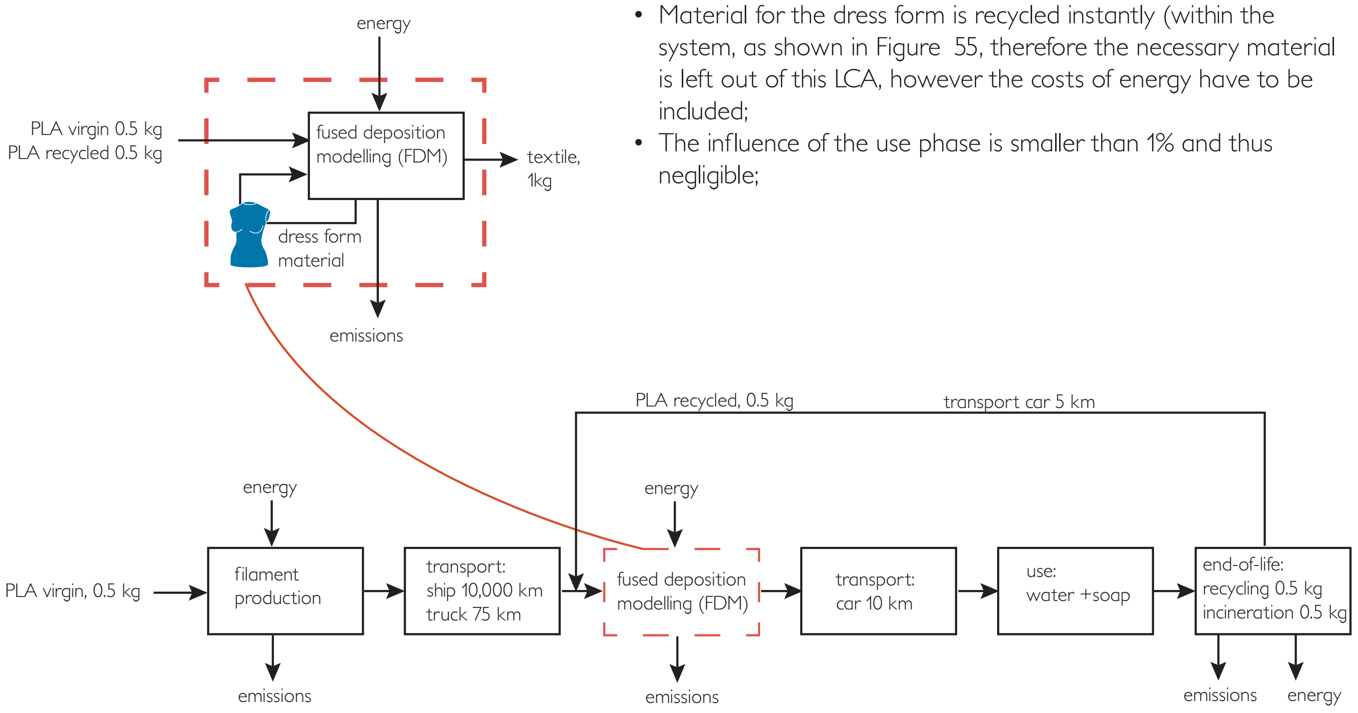


FIGURE 55. SCENARIO 3

15.7.3 METHOD

The environmental impact of the product is calculated using eco-costs. Data for the eco-costs are obtained from www.ecocostvalue.com. For FDM, no eco-cost data were available (yet), therefore these have been calculated by means of measuring the required energy with a kilowatt-hour meter and calculating the eco-costs as described in [Vogtländer, 2012]. The energy measurements for the FDM process are presented in appendix D2.

15.7.4 RESULTS

The detailed LCA calculations can be found in appendix D2. Figure 56 shows the eco-costs of the scenario.

The total eco-costs are €3.69. The largest part of the costs is determined by the FDM process (51%), followed by the costs of the consumer transport by passenger car (31%).

15.7.5 COMPARISON

The eco-costs for the first scenario are comparable to those of woven textiles with a yarn thickness of 300 dtex, which range between €3.50 and €5.00 [Van der Velden et al., 2014]. Compared to the LCA executed earlier in this report, the eco-costs are considerably lower, both for the base material and the production process. This suggest that FDM has less of an environmental impact than SLS. The base material plays a large role in this, since PLA is a renewable, biodegradable resource, it has a better environmental score than nylon.

Interestingly, a large portion of the eco-costs for the first scenario are determined by the transport from the consumer to and from the store. Although this can be relativized by the fact that this is a conservative estimate that will most likely not be the case for each consumer (e.g. some may live closer, come by bicycle or public transportation), it would suggest that perhaps ordering the product online and having it send home will be less of an environmental burden.

Currently, for the use phase it is assumed that the product is cleaned by water and soap, which has a negligible impact on the final eco-costs. If it is possible to develop a material that is machine-washable, this would mean that the impact of the use phase can no longer be neglected, which would add approximately €0.50 to the eco-costs [Van der Velden et al., 2014].

The ecodesign strategy wheel for this scenario is shown in Figure 57. The product scores well, improvements can be made for the distribution and transport, and the initial lifetime.

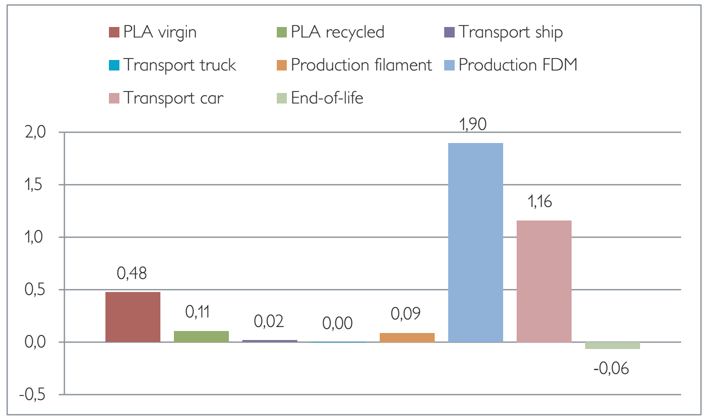
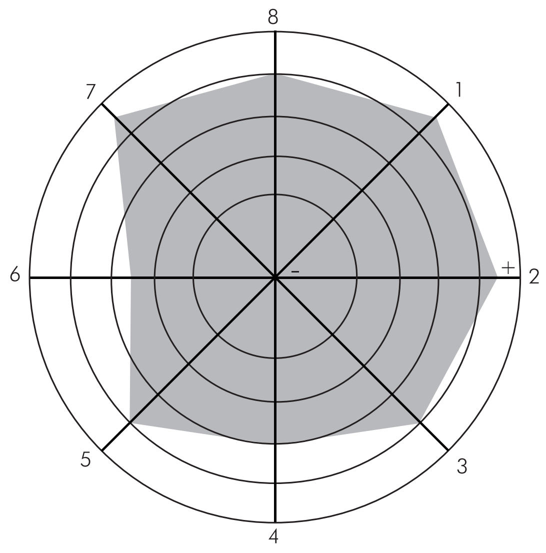


FIGURE 56. ECO-COSTS OF SC. 3



1. CHOICE OF MATERIALS
2. MATERIAL REDUCTION
3. PRODUCTION METHOD
4. DISTRIBUTION AND TRANSPORT
5. IMPACT OF USE
6. INITIAL LIFETIME
7. END OF LIFE
8. ALTERNATIVE FUNCTION

FIGURE 57. ECODESIGN STRATEGY WHEEL FOR SC. 3

16. PROTOTYPING

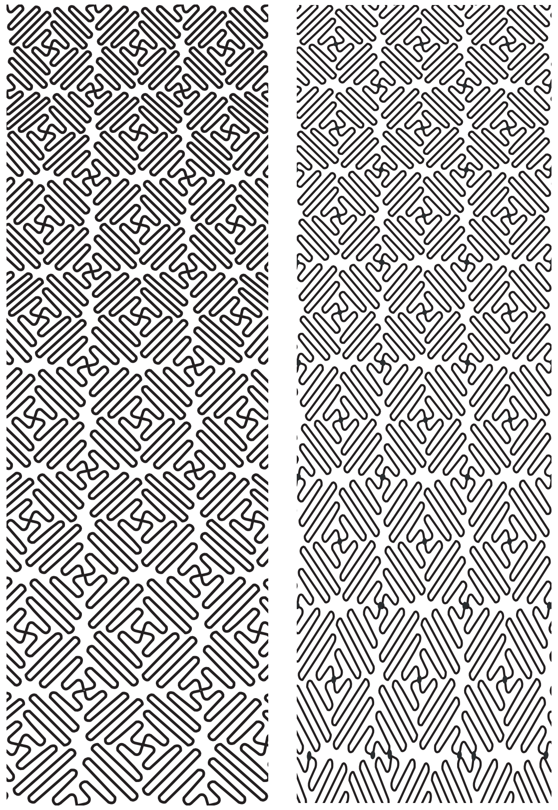


FIGURE 59. ORIGINAL GRADIENT VS SIMPLIFIED GRADIENT

FIGURE 58. SHAPE OF THE CORSELET MADE WITH TAPE

The material was developed with the versatility of 3D printing in mind, meaning that the material is suitable for small adaptations in order to change its properties. As discussed in the previous chapter, this means that there is no definite way in which the material should be applied to a product, this can and should differ per design and per product. With this in mind, it was found useful to create a prototype of the final design, in order to test the applicability of the material and to find possible improvements for the product. Since the cellulose blend could not successfully be printed, the prototype is made of PLA. The downside of this is that it is not feasible to test whether the design solves the comfort issues mentioned earlier, as these may just have been replaced by the discomfort of the material. Since the design is meant to be custom-made, the prototype is also made to fit one specific person.

In this chapter, the process of the creation of the prototype is discussed, together with the difficulties that were found along the way. Finally, a number of recommendations for the final design are given.

16.1 PROTOTYPING PROCESS

The prototype needed to be produced with the equipment that was available, which meant that it could not be printed in one piece, but had to be constructed of flat pattern pieces. A model of a human torso was used as the basis for the pattern, which was obtained by making a copy of the body of a volunteer out of tape and filling it with old newspapers.

The pattern needed to be designed to exactly fit the mannequin torso. Therefore, the mannequin body was wrapped in a T-shirt and consequently wrapped in tape, in the shape of the corselet as shown in Figure 58. This was cut off the body, and divided into eight pieces: two front panels, two back panels, two side panels and two cups. Special attention was paid to make sure the width of each panel would fit onto the build platform of the 3D printer. The pattern pieces were flattened and scanned, after which they were outlined in Adobe Illustrator.

The fastest way to apply the pattern of the material to the panel pieces was found to manually add them in Adobe Illustrator. For the body itself, the square pattern was used, while the hexagonal pattern was used for the cups, because of their rounded shape. A few simplifications were made to the design in order for it to be drawn manually: the gradient in size was limited to stretching the pattern in the y-direction only, instead of in the x- and y-direction (as shown in “Figure 59. original gradient vs simplified gradient” on page 106); some displacements in the rhythm of the pattern were necessary to fit the pattern across; the panels for the bodice were divided into two pieces in order to fit onto the build platform of the printer. The exploded pattern as drawn in Adobe Illustrator is presented in Figure 60.

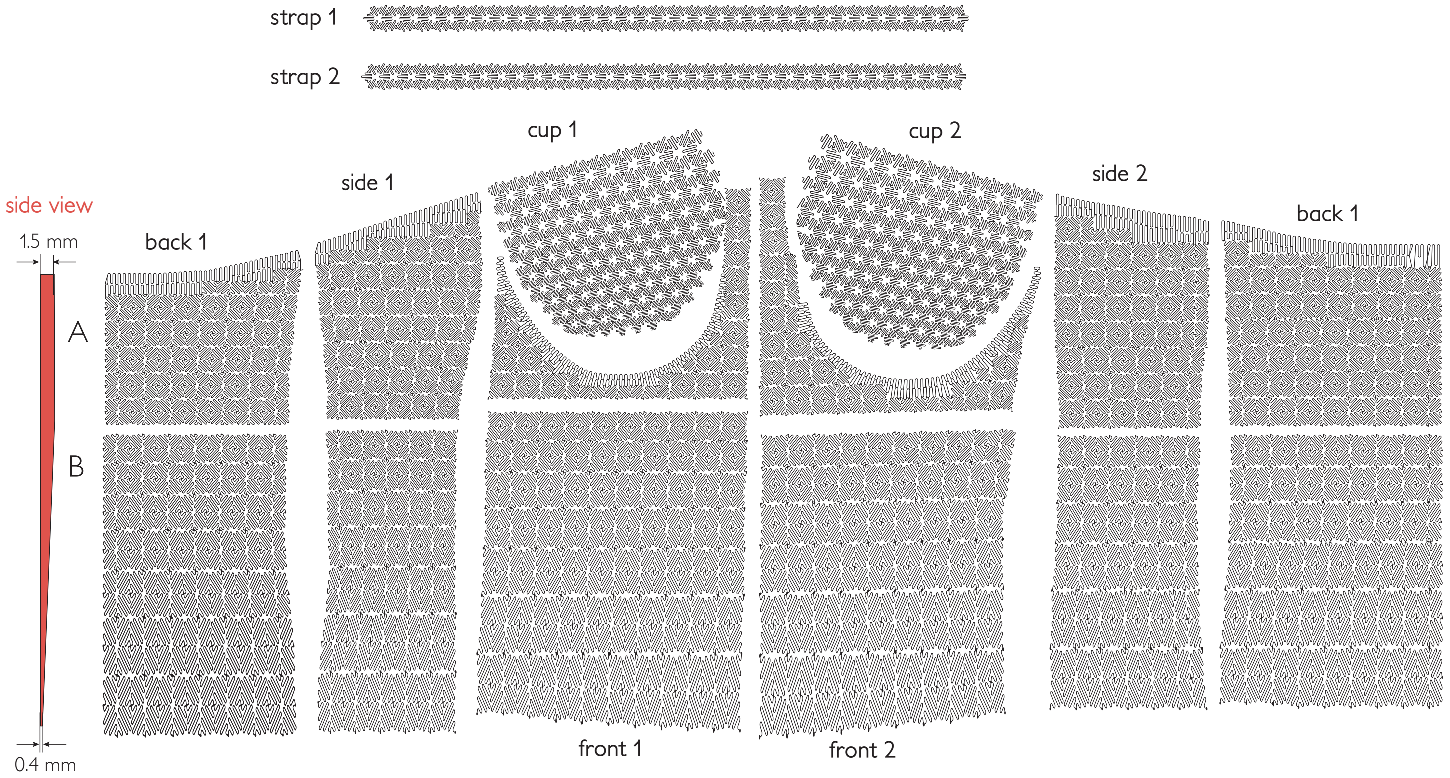


FIGURE 60. EXPLODED VIEW OF THE FLAT PATTERN

Although the pattern is suitable for a gradient in both directions, without a computer-generated model this is nearly impossible to achieve. Therefore, this effect was mimicked by stretching the pattern in one direction, which also accomplished a softer, more flexible feeling, although this also creates a different bending direction and it is less aesthetically pleasing. The vector illustrations were transformed into 3D-models, by importing them into CAD software. The best results were obtained by exporting them as a Scalable Vector Graphic (.svg) and extruding them in the simple, free CAD-program Tinkercad (www.tinkercad.com). The benefits of this program are that it is not bothered by small gaps in the vector drawing (as for instance Solidworks is), and that the stl export is a small file, which is easier to slice. A gradient was applied in thickness of the panel pieces, which is visualized in Figure 60.

Some print tests were performed using both Makerbot printers and Ultimaker printers. Based on the results of these tests, it was decided to use an Ultimaker 2 printer for the final panels.

A number of problems and difficulties were encountered during the prototyping process:

- Generation of the pattern; since the pattern had to be drawn by hand, not only was it a rather long process, but this also means there were a number of imperfections in the final pattern that could not be improved.
- Conversion steps; the conversion process to create a file that can be printed is rather long and tedious. It is depicted in Figure 61. From vector drawing, the file is converted to .svg, extruded and exported as .stl and finally sliced as .gcode or .x3g. The number of steps means that it is difficult to make changes in the file, since the entire process needs to be repeated in that case. Also, the pattern results in large files, that were too complex to handle for some programs.
- Slicing times; especially the software from Makerbot took a long time slicing the stl-files, up to four hours for one panel. It was found that decreasing the size of the stl decreased the slicing time, as well as rotating the position of the panel on the build platform, so that the lines of the pattern corresponded with the horizontal and vertical lines of the build platform.
- Printing the model; a problem with both Makerbot and Ultimaker printers was that the printing quality is not constant; some layers print perfectly, while others print with a lot of mistakes. No obvious cause could be found for this problem, except for the complexity of the pattern itself.
- Adhesion to build platform; the build platform of the Ultimaker 2 is heated, therefore only a glue stick is necessary to adhere the print to the platform. However, in some cases the adhesion of the glue is not enough, causing the print to loosen and wrap around the nozzle. To solve this, the print speed and the layer thickness for the first layer can be decreased and increased, respectively.
- Removing the print from the build platform; this was found to be especially problematic when printing on the blue tape. Three solutions were tried: removing the tape while the model was still on it; using a spatula to pry the model of; and using hot water to soak the model of. None of these succeeded in keeping the model intact: the first two methods caused tearing of the connections in the pattern, while the latter method caused the model to deform in the hot water.

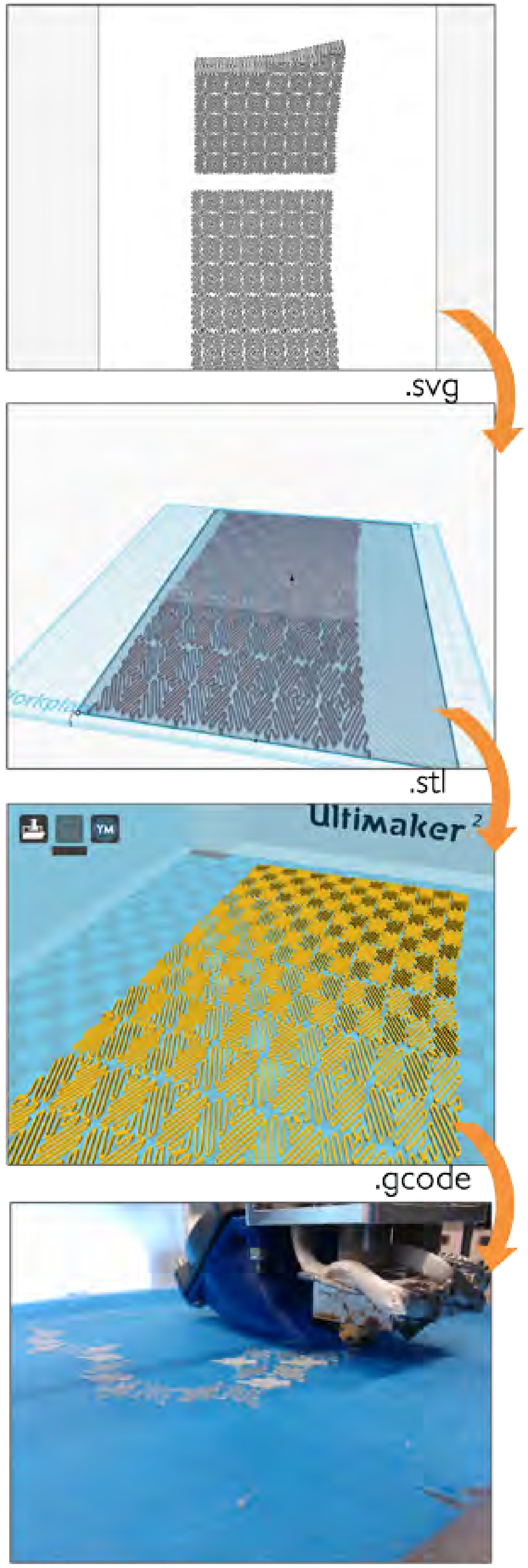


FIGURE 61. CONVERSION PROCESS

16.1.1 CONSTRUCTION

The parts of the prototype where printed using the following settings, which were determined by means of trial and error:

- 1st layer thickness: 0.15 mm, speed: 15 mm/s
- Layer thickness: 0.15 mm, speed: 30 mm/s

Table 07 shows the required material weight and length, the estimated build time and the actual build time of each piece. After printing, the parts were fitted onto the dress form and attached to each other with a combination of yarn and 'soldering' them together. A better fit was created by shaping the prototype to the dress form with a blow dryer.

16.2 EVALUATION

The final prototype is shown in Figure 62. More images can be found in appendix L. The goal of the prototype was to illustrate the applicability of the MSP, to test the feasibility of the MSP as a textile, and to evaluate whether it was suitable as a bra.

It was found that the applicability of the MSP was sufficiently demonstrated. It is clearly noticeable where the MSP is more flexible and where it is more supportive, and it has shown that these differences can be used in the way that was intended by the design.

The MSP shows a lot of imperfections due to printing. Some parts are not sufficiently connected, and some were show a lot of printing imperfections. They are fragile points for the prototype, in addition to the natural fragility of the material. Although it is not very noticeable, it decreases the amount of support that the product gives.

The cups were found insufficiently comfortable, which can be solved by a number of suggestions. The easiest solution would be to add an extra layer of traditional fabric in the cups, as it is quite common in garment design to utilize multiple textiles with different properties. Another option would be to add an extra printed layer, with a larger spring design, which has a softer feel but provides less support. However, the cups provided good support: from which it can be concluded that the MSP with a thickness of 1.5 mm and a pattern size of 20 mm across sufficed (although this may not be the case for larger cup sizes; which should be tested more extensively). It should be noted that the pattern pieces of the cups were already somewhat stretched when attached to the rest of the bra; so that the cups would not be too elastic and hence more supportive. This too should be adjusted per size and preference.

The gradient applied in the cups was linear, although from the prototype it was found that the sides of the cups should be stronger as well; these thin connections broke due to the tension put on them, therefore a radial gradient would be more suitable. This will also provide for a stronger connection with the straps.

The upper part of the corselet that fulfilled the function of the upper- and underband was supportive enough. However, since the prototype was too fragile to wear for an extended period of time,

FIGURE 62. FINAL PROTOTYPE

	Material weight	Material length	Estimated build time	Actual build time
Back 1A*	11 g	1.37 m	1 hour 49 min	3 hours
Back 1B*	16 g	1.97 m	2 hours 44 min	3.5 hours
Side 1A*	18 g	2.31 m	2 hours 52 min	3.5 hours
Side 1B	10 g	1.29 m	1 hour 36 min	2 hours
Front 1A*	9 g	1.19 m	1 hour 26 min	2 hours
Front 1B	22 g	2.77 m	3 hours 22 min	03:10
Front 2A*	11 g	1.37 m	1 hour 37 min	2 hours
Front 2B*	19 g	2.36 m	2 hours 59 min	3:09
Side 2A*	17 g	2.17 m	2 hours 40 min	3 hours
Side 2B	11 g	1.37 m	1 hour 41 min	2 hours
Back 2A	20 g	2.54 m	2 hours 52 min	3 hours
Back 2B	16 g	2.00 m	2 hours 34 min	02:51
Cup (2x)	17 g	2.09 m	2 hours 30 min	02:30
Straps	17 g	2.11 m	2 hours 14 min	03:37
Total	**231 g**	**26.91 m**	**32 hours 56 min**	**39 hours 17 min**

*different slicing settings, due to an unclean printer: initial layer thickness 0.20 mm, speed 15 mm/s, flow 150%

TABLE 07. BUILD DATA PER PART

more testing should confirm whether this would also be the case when worn for the entire day for instance.

The straps were not strong enough to fulfil their function, partly due to the low tear-resistance of the material. The straps have a highly supportive function: therefore they need to resist a lot of stress, although at the same time they must be elastic enough to be put on across the shoulder. PLA as a material was not suitable for both these functions. In addition, the hard edges of the material can cut in the skin, which can cause discomfort. A different, more flexible material with a higher tear-resistance might be more suitable to prevent these problems.

16.3 CONCLUSION

The prototype has shown that the MSP is suitable to be applied in bras, although PLA as a material is not. This is not only caused by the rougher, harder feel of the material, but also since it is not strong enough to be worn for a longer period of time. However, it was sufficient to demonstrate the applicability of the MSP and to test its function as a bra. The support provided by the design is good. Unfortunately, it was not possible to test whether discomforts caused by regular bras were diminished, since the material itself was not comfortable. It is recommended that this will be more extensively tested with the intended material for the MSP, and that the design is optimised in collaboration with an experienced bra designer.

THE ARALIA WORN IN ITS CONTEXT

17. CONCLUSIONS

This part has shown the development of a final MSP concept, and it has been applied to a final product design. The current materials that can be processed by AM were found to not sufficiently fit with the vision, which is why it was thought to be most valuable to search for other materials that have the potential to be 3D printed. Obviously, due to the limited time, it was not possible to fully develop this material. However, the properties of the sample as it is created have a better fit to the vision than the other 3D printable materials that have been tested.

As a result, the MSP is intriguing because of its geometric pattern, the surprising flexibility of its feeling when it is touched, and lastly because of the fact that it is made by 3D printing. The MSP is familiar because of its surface feeling, in which the natural fibers can be recognized. So, when worn on the skin, the MSP will not be obtrusive.

The results of the LCA analysis have shown promising results. Although the material concept was replaced by PLA, this should not make a crucial difference since cellulose is a relatively environmentally friendly material, especially if fibers are kept intact. The total eco-costs for 1 kg of 3D printed textile were comparable to those of traditional textiles. This was partly due to the energy requirements for the FDM process, which were lower than expected (considering that high energy costs are often contributed to AM). Even more so, the energy requirements are relative to the printing speed of the printer, which were very low for the prototype (15 mm/s), and with the advancements of the technology the required energy is expected to drop. Therefore, these results seem to indicate that 3D printing may actually serve as a sustainable replacement for textile production.

The product proposal for the MSP is a bra. This was found the most meaningful product direction due to the following factors:

- The properties of the MSP: it resembles lace, is slightly feminine, and elastic. In addition, the proposed cellulose blend has soft, velvet-like surface properties;
- The fact that 3D printing can create personalized products to the exact size required;
- The fact that the MSP in combination with 3D printing can create property gradients: these are extremely suitable to replace the large number of parts that are currently required for bras in order to create sufficient support.

The design of the product was slightly altered to a corselet, in order to demonstrate the softer properties of the MSP as well. Different alterations of the MSP were applied to fulfil the necessary functions. It is suggested that the final design of this product (and of other, related products such as bras with different functions) should be performed in collaboration with a (senior) bra designer, since they are specialized in the design of bras and could optimise the comfort and functions of the bra.

The prototype was made to illustrate the application of the MSP and to test its suitability as a bra. It was found that the tensile strength of the PLA is too low, and it is too brittle, to make it fully wearable, since it is prone to fracturing. The prototype has shown that the MSP is suitable to be applied in bras, although PLA as a material is not. This is not only caused by the rougher, harder feel of the material, but also since it is not strong enough to be worn for a longer period of time. However, it was sufficient to demonstrate the applicability of the MSP and to test its function as a bra. The support provided by the design is good. Unfortunately, it was not possible to test whether discomforts caused by regular bras were diminished, since the material itself was not comfortable.

An important conclusion is that a few fractures in the MSP do not diminish their function, although the supportive function will be decreased. This could elongate the life span of the product. However, the fractures in the PLA material are almost impossible to repair, which means that the fractures will only accumulate and finally render the product useless. As such, it can be concluded that PLA is not suitable as a substitute material. It is important that the future material will be able to withstand the forces applied to the MSP, and offers opportunities to repair fractures in the material.

In addition, since the material is quite hard the edges of the pattern can cut into the skin, however, this will be solved when a more flexible material is applied (such as the cellulose blend). It was also concluded that the cups were not comfortable enough, they require an additional layer of softer material in order to not irritate the skin. As a temporary, in-between solution, it would be possible to print the MSP in PLA on a traditional textile material, which makes it less prone to breaking, and provides softer surface properties; or to print it with a flexible PLA material (although this was not possible to test with the available printers).

The vision for the product was summarized in the statement "I want people to have an attachment to their 3D printed garment, by creating a personally engaging experience, like the act of blowing bubbles". The attachment is created by making the bra exactly to size, adjusted to the requirements of the user. A better fit will cause less irritation, which makes for one less reason to dispose of the garment quickly, and will make it a beloved and appreciated item in the closet. The engaging experience is provided by the MSP itself, its movability and elasticity make it engaging to feel. Its appearance makes people want to touch it; since it is not like any other material, and it keeps being interesting to interact with, just like bubbles.

THE ARALIA WORN IN ITS CONTEXT

THE ARALIA WORN IN ITS CONTEXT

PART V

RECOMMENDATIONS & EVALUATION

In the final part of this thesis, some recommendations are given for the future development of 3D printed textiles, as well as an evaluation of the applied process in regards to this project.

18. RECOMMENDATIONS

18.1 MSP

It should be clear that the MSP, as it is presented in this thesis, is not yet ready for production. It is not surprising that this is the case, seeing as the category of 3D printed textiles is not yet established, and a large part of the process was understanding and defining its boundaries. However, the MSP does function as a proof of concept: it shows the potential of what 3D printed textiles could be like, even in this early stage of development. As a main recommendation, it is advised to consider 3D printed textiles a category of their own, which has the ability to offer more opportunities than traditional textiles.

The MSP developed in this project should not be considered as *the* solution for 3D printed textiles, but rather as an example of a 3D printed textile, just as there are more types of traditional textiles.
However, there are a number of aspects that should be developed further in order for this MSP to be applied to a garment. This development should focus on two traits: developing the material in order to be used in the AM process, and optimising it for use as a textile material.

The components of the material blend should be optimised. Although the experiential properties of the material should be similar to the proposed material blend, the components of the blend should not be the same, since they do not fulfil the material requirements. The main characteristic of the material should be the cellulose fibers. Tests should be done to establish what the optimal length of the fibers is, and what source they should come from (e.g. wood, cotton linters). More development is necessary to develop the optimum (combination of) binder(s). The flexibility of the material should be kept, since this creates and overall softer feel for the MSP, but the acrylic was found not to be sufficient for use as textile. The binder(s) should provide the following aspects in addition:

- Extrusion: enabling the fibers to slide past each other in order to be extruded;
- Durability: the material should be developed so that it can withstand the forces that are caused by its functionality as a garment, in order to have a long life span. Part of this is making it strong enough not to break, and part is making sure that it will not stretch out over time.
- Safety: since the material is to be worn close to the skin, it should not contain any harmful or poisonous substances;
- Colour: the material should be producible in different colours;
- Maintenance: for the convenience of the user, it is preferred that the material is machine washable, and in addition: that it can be repaired (e.g. with thread and needle) in order to prolong its life span.

A proposed material blend that would be interesting to test is for instance cellulose fibers in combination with a PLA + PE blend (which will make the PLA more flexible), or a PLA calcium carbonate blend (which will make the material more ductile) [R. Koster, pers.comm.,15/08/14].

One particular characteristic of the MSP is that due to its pattern, the material cannot be cut in any shape. The smaller the size of the pattern, the less of an issue this becomes. Still, it is not advised to use the material in the same way as traditional fabrics, but only when it can be generated by a CAD model.

18.2 3D PRINTED TEXTILES

The MSP as it is designed now is bound by current technological limitations, which becomes most clear by the fact that its technical characteristics are not sufficient to be used as a textile. A number of suggestions can be made in order to develop future 3D printed textiles that relate mostly to two aspects: the available resolution of 3D printers, and the materials available for 3D printing.

First, as was conclude in the chapter regarding textiles, the hierarchical complexity that is responsible for the desirable properties in textiles, can be produced because of the small macrostructure of the components, i.e. fibers. It has also been found in this thesis that 3D printed textiles behave more like regular textiles when their macrostructure is decreased. Therefore, it would be interesting to develop future 3D printed textiles with a macrostructure that is smaller than can currently be produced.

However, part of the reason why textiles are desirable for garments is because they consist of multiple levels, i.e. their hierarchical structure itself. In order for 3D printed textiles to obtain the same properties of textiles, they will have to mimic this complex structure. In my opinion, this can be accomplished in two ways: the first is being able to print small scale structures within larger structures, to mimic the effect that is now created by for instance fibers in yarn, although this would mean the resolution of printers should improve enormously. This structure would then ideally combine two different structures, such as multiple assemblies and thin structures. The second, which I think is more feasible, is mimicking the hierarchical structure by means of the input material, as has been done in this thesis. In that case, the material that is deposited by the printer should already possess some kind of structure, after which it is built into a second structure by the printer. One option to accomplish this is by integrating fibers into the material, as has been done with the cellulose blend, but it would also be interesting if materials could be developed that have certain porosity in their structure, or consist of multiple strands etc. This is elaborated more in the next section.

Second, the materials that are available for 3D printing are still limited. From the materials that could be tested during this project, none were found sufficient for a textile application. Seeing as material developments will most likely progress in the future, there is no doubt that stronger, more flexible and durable materials will be developed, and it will be interesting to test them for 3D printed textiles. However, in the end it is recommended that materials will be designed and developed specifically for the application of textiles, since these have rather specific requirements. One interesting development direction would be 3D printing of natural materials.
Although in this thesis the attempt was made to print cellulose fibers, it was shown that there are many other fiber materials and structures that could potentially inspire AM materials for textiles. By studying nature for inspiration, new and interesting materials and structures could potentially be found. One example is the manner in which silk worms produce silk: a sticky substance is used to attach filaments together in certain ways, which would be interesting if this could be mimicked by AM.

18.3 PRINTING PROCESSES

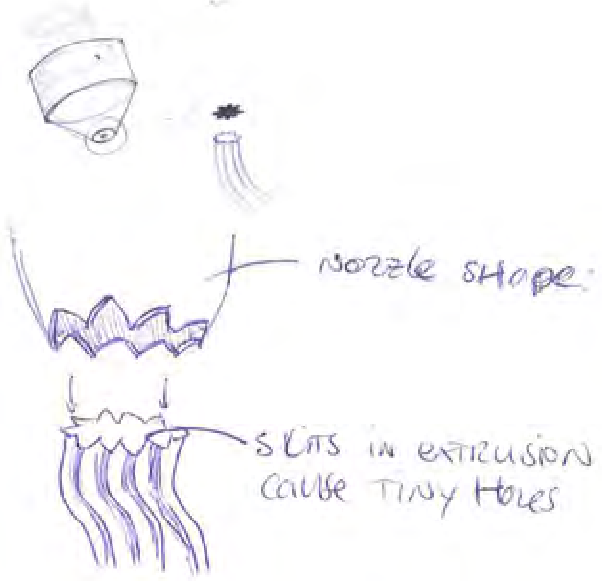


FIGURE 63. NOZZLE WITH ´RIBBED´ HOLE

FIGURE 64. NOZZLE WITH MULTIPLE HOLES

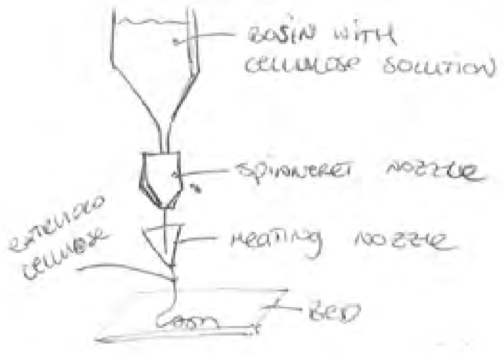


FIGURE 65. AM BASED ON THE CELLULOSE REGENERATION PROCESS

The previous section has given a number of recommendations regarding possible structures and materials for future 3D printed textiles. However, also certain suggestions for AM processes can be given. As has been remarked earlier in this thesis, the production of textiles has come about by many years of optimization and specialization. As current AM processes have not been specifically developed to produce textiles, it may offer some opportunities to develop such a process specifically for the production of textiles. In order to do so, I would suggest investigating certain processes that are used during textile production that show potential for AM. The development should be driven by the question what types of materials and structures we would want to print, and finding ways to do so, instead of driving the development from the nature of the processes.

One example of this is the process of regenerating cellulose, which is briefly explained earlier in this thesis. During this process, a solution of cellulose is forced through a spinneret to produce long, thin filaments. If the same could be done in an additive process, it would be possible to build structures consisting of extremely thin filaments, resembling yarn. Obviously, the two processes are completely different from each other, but it would for instance be interesting to test the potential of such a process, as sketched in Figure 65.

Additionally, it would be interesting to experiment more with nozzle sizes and shapes. For instance in order to create a porous structure as mentioned in the previous section, it would be interesting to test a nozzle with multiple holes, as sketched in Figure 64, or with a ribbed hole, as sketched in Figure 63. For these experiments, some adaptations to the process would most likely be necessary, for example a higher pressure would likely be required.

Besides the process itself, the process of transferring the file to the printer should be simplified. Especially for complex structures and hierarchies, it is at the moment almost impossible to create these onto complex, freeform surfaces. Software should be developed that can easily map a complex pattern on these surfaces, in addition to applying size-gradients and corrections.

Also, it was found that fashion designers have trouble thinking in 3D, partly due to the current education system. However, it does not seem impossible to develop software that would make it easier for fashion designers to use AM. For instance, a system could be imagined where the fashion designers would sketch the garments as they usually do in 2D pattern pieces, which can then be uploaded in the software. The software maps them visually around a body shape, and integrates them as one model. From there, adaptations could still be made to optimise the garment, apply shape gradients etc. The downside to such a system is that the steps are redundant: the model is transformed from a 3D sketch to a 2D pattern to a 3D model. A more efficient approach, although possibly harder to integrate, would be a system that works easily with surfaces, which can be wrapped and adjusted to size for an (imported) 3D body shape, and to which the pattern can be applied easily.

19. EVALUATION

This thesis has shown the application of an MDD method [Karana et al., in review] to a design process where AM is the primary production method. The goal of the design project was to create a meaningful application using 3D Printed textiles. Since the method was applied to not only a material, but a combination of material, structure and process, the process was somewhat different.

UNDERSTANDING THE MATERIAL
For the first step, it was found that not only an understanding of the material is necessary, but an understanding of the MSP as a unit and of all separate aspects was necessary, including how they influence each other. It was also necessary to research and define the boundaries of the MSP. Since 3D printed textiles are only starting as a material category, a great part of the process was focused on finding out what 3D printed textiles could be and should be.

The current state of technology has also had a great influence on the process. It is important to be able to create and feel samples, in order to evaluate them. However, the resolutions of the printing process regarding structure, the available materials and even available software were limiting the creation of samples, because it was sometimes just not possible to create a design within reasonable time limits (since it was not always sure whether the design would even work as a 3D printed textile or fit the vision). Therefore, I would say that the result of this project reflects the possibilities that AM currently offers.

MSP means that all combinations of material, structure and process should be explored; if one is set, the two others might vary. This means there are numerous possibilities, since for 3D printing the process dictates the materials that can be used and the resolution/ tolerances of the structure. Therefore, these three aspects are always influencing each other and should not be considered separately.

VISION
The goal of the vision in the MDD process is to express the role of the material in the product and a unique user experience [Karana et al., in review]. Accordingly, the vision should be used to develop material concepts as a driver. The creation of the vision was the part I struggled with the most. I hindsight, I think this was caused by the fact that although the vision focused on a material interaction, the context of use and requirements that came from this context were already enough to develop a strong vision on. Therefore, I think the vision is in line with the findings that came from the context, but it is not on the abstract level that it should have been on according to MDD.

The vision also had a different role: it was used to evaluate the material categories that had been determined before; to choose one that seemed most promising; and finally to develop it further to fit the requirements. If this had not been the case, the unlimited possibilities would have been too overwhelming; therefore this step was necessary in order to define some boundaries for the project. In addition, the vision was also used as inspiration for a future printing process.

Since the final product application was not supposed to be new and out-of-the box, the vision was mostly used to think of a future version that the material should be but that could not be created at this moment. In that respect, I think it helped in trying to see beyond the technology as it is today to what it could be in the future, which in turn reflected on the proposal of using a material that cannot be printed at this moment.

CELLULOSE PROPOSAL

This material proposal was for a large part driven by the vision. The question became: what type of material would I want to use for a 3D printed textile, instead of what was available to print. The answer to this was that I wanted to print a material in fiber form or a 'non-woven', which has driven the experiments in order to find out a possible way to print such a material. I think this question would be useful for the development of 3D printed textiles in the future, as discussed in the recommendations section. I feel that the cellulose material proposal was the missing link for the MSP in respect to the vision, as well as providing a future direction for research that goes beyond the limits of what we can print today.

This might also be a valuable addition to the MDD process: creating a vision of what the material should be like in an ideal situation, as driven by the abstract metaphor, but which lets go of the technical limitations of the present, and imagines a world in which it would be possible to create anything. This material, that does not (and perhaps cannot) exist in the present, could be made more concrete by referencing other materials and technologies, in order to make assumptions on its feasibility in the future.

INFLUENCE OF AM ON THE PROCESS

The fact that the final product category, garments, was already set at the beginning of the process made it easier to cope with the almost unlimited possibilities. The application was kept in mind since the beginning of the process, which has been reflected by the literature review, vision and material requirements. The goal became exploring how AM could be used to enrich the defined product category, rather than replace it blindly. It was therefore necessary to look at the opportunities of AM, in addition to the requirements of the product (category) and seeing how they can be used to improve each other.

For the MDD method, this meant that it was exploratory, since the limits of this new product category needed to be found and defined first. The same would be true if AM would be used to replace a different material category. If there was no material category, in my opinion it would not make sense to set AM as a primary production process, since this would be just as general as saying "design something that is injection moulded".

AM as a primary production process offers the opportunity of creating personalized products, which has influenced the final material concept. Rather than being one fixed material, the material can be locally varied to create property gradients, which results in a range of slightly different materials that all fit the intended vision. Early in the process the decision was already made that this aspect should be used for the final product. However, this did mean that again a set of boundaries needed to be defined that encapsulated the amount of variation the material could have, which resulted in a range of solutions.

Since AM was the driver for the project, the normal order of the design process changed: instead of designing and embodying a garment, and then choosing the production processes that are suitable for the design, in this case it was the other way around: first discovering and designing what the textile could be like, and then applying it in the production of a garment. I think this resulted in a desire to make the MSP as simple as possible, because it could not be created for a specialized garment. But in addition, I think this created the possibility of having a more objective view towards 3D printed textiles, which also allowed me to fully utilize the opportunities of AM and analysing where it could truly be of value.

20. GLOSSARY

AM – Additive Manufacturing, a process in which a product is produced in an additive way by means of a computer generated model (also 3D printing)

Benchmarking – method to position a product amongst similar or alternative products

Eco-costs – the costs that are necessary to reduce the environmental impact to a level that the earth can sustain

Emotional experience – feelings and emotions elicited by a material

Experience of meaning – the meaning(s) that are attached to a material or product by the user

Experiential characteristics - the properties of a material that influence how a material is experienced, which can be divided into aesthetics, meanings and emotions

FDM – Fused Deposition Modelling, an additive technology in which a molten plastic is deposited into a desired shape

FGM – functionally graded materials, heterogeneous materials produced by additive manufacturing

LCA – Life Cycle Analysis, a method used to determine the environmental impact of a product for each stage of the life cycle for a chosen scenario

Linters – the shortest cotton fibers that cannot be used to produce yarn

Material experience – made up of aesthetic, meaning and emotional experience

Material Extrusion - an additive technology in which a material is extruded to form the layers of the shape

Materials Experience Vision – expresses the envisioned role of a material for a unique user experience

MDD – Meaning Driven Design, a design method in which a material is the main driver

MDMS – Meaning Driven Material Selection, a method used to explore material qualities related to certain meanings

MoM – Meanings of Materials, a model used to visualize the results of the MDMS method, which takes into account the material, product and user.

MSP – term used to describe a material that is actually a function of its material, structure and process

Multiple assemblies – a term used to refer to a structure that consists of discrete bodies

PLA – biodegradable plastic, commonly used in the Fused Deposition Modelling process

Sensorial experience – how a material influences our senses

SLA – Stereolithografie, an additive technology in which a UV-light cures a photopolymer in a desired shape

Slenderness ratio – length to thickness ratio of a fiber

SLS – Selective Laser Sintering, an additive technology in which a laser sinters powder in a desired shape

TangoBlack – trade name for a black, flexible material that can be processed by means of Polyjet technology

Technical characteristics – the properties of a material that determine its functional performance

Thin structures – a term used to refer to a structure that consists of one part and obtains flexible properties due to thin(ner) parts in the structure

21. REFERENCES

3D Systems, Inc. (2014). *Stereolithography (SLA).* Accessed via: http://www.3dsystems.com/quickparts/prototyping-pre-production/stereolithography-sla, on 24/03/14.

3Ders.org (2014). *3D printed flexible textiles – a stitch towards personalized clothing* [Online] 3Ders.org. Accessed via: http://www.3ders.org/articles/20140128-3D printed-flexible-textiles-a-stitch-toward-personalized-clothing.html on 27/03/14.

Altas, S. and Ozgen, B. (2013). Investigation of Fabric Properties Woven with Different Fabrics. *Tekstilec,* 56(2), 117-122. Accessed via: http://www.tekstilec.si/wp-content/uploads/2013/06/Raziskava-lastnosti-tkanin-iz-razli_nih-vlaken.pdf on 17/03/14.

Bastion, A. (2014). *3D Printed Mesostructured Materials*. Andreas Bastian, viewed 20/08/14 via http://www.andreasbastian.com/blog/3D printed-mesostructured-materials/.

Bingham, G.A., Hague, R.J.M., Tuck, C.J., Long, A.C., Crookston, J.J. & Sherburn, M.N. (2007). Rapid Manufactured Textiles. *International Journal of Computer Intergrated Manufacturing,* Vol.20, Issue 1 (96-105). Accessed via: http://www.tandfonline.com/doi/abs/10.1080/09511920600690434, on 20/03/14.

Blom, J. (2000). Personalization – A Taxonomy. *CHI EA,* Chi'00, 313-314. Accessed via: http://dl.acm.org/citation.cfm?id=633483, on 16/05/14.

Carpi, F., Pucciani, M. and De Rossi, D. (2007). 'Mechanical Models and Actuation Technologies for Active Fabrics', in Duquesne, S., Magniez, C. and Camino, G. (ed.) *Multifunctional Barriers for Flexible Structure*, Springer Series in Material Science, Springer Berlin Heidelberg New York.

Carpi, F., Pucciani, M. and De Rossi, D. (2007). 'Mechanical Models and Actuation Technologies for Active Fabrics: A Brief Survey of the State of the Art' in Duquesne, S., Magniez, C. and Camino, G. (ed.) (2007). *Multifunctional Barriers for Flexible Structure, Springer Series in Material Science,* Springer Berlin Heidelberg New York, p151-168.

Chan, C.Y.C., Yu, W.W.M. and Newton, E. (2001). Evaluation and analysis of bra design. *The Design Journal,* 4:3 (33-40).

Chou, C. and Conley, C. (2009). Identifying Products That Enable Engaging Experiences - Searching Cases for Theory Development. *International Association of Societies of Design Research* 2009 (IASDR 09), Seoul, South Korea.

Click NL (2014). *Crafting Wearables* [Online] Click NL|Next Fashion. Accessed via http://www.clicknl.nl/nextfashion/2013/04/23/crafting-wearables-2/?lang=en, on 23/04/14.

Coevert, A. (2014). 'In Amsterdam wordt momenteel een 3D-grachtenpand geprint', NRC Handelsblad, Beste van het web, 16 maart 2014. Available from http://www.nrc.nl.

Continuum Fashion (n.d.). *N12 Bikini* [Online] Continuum Fashion. Accessed via: http://www.continuumfashion.com/N12.php, on 27/03/14.

Crookston, J.J., Long, A.C., Bingham, G.A., Hague, R.J.M. (2008). Finite-element modelling of mechanical behaviour of rapid manudactured textiles. *Journal of Materials Design and Applications,* Vol. 222:29, Part L.

Duquesne, S., Magniez, C. and Camino, G. (ed.) (2007). *Multifunctional Barriers for Flexible Structure*, Springer Series in Material Science, Springer Berlin Heidelberg New York.

Electroloom (2014). *The World's First Personal 3D Printer For Clothes* [Online] Electroloom. Accessed via http://www.electroloom.com/ on 27/03/14.

Emirhanova, N. and Kavusturan, Y. (2008). Effects of Knit Structure on the Dimensional and Physical Properties of Winter Outerwear Knitted Fabrics. *Fibres & Textiles in Eastern Europe,* Vol.16, No. 2(67).

Fabrican Ltd (2007). *Technology* [Online]. Fabrican Ltd. Accessed via: http://www.fabricanltd.com/about-us.php?category=Technology on 21/04/14.

Fletcher, K. (2000). Why we need clothes. *EcoDesign,* Vol 8, No 1:34

Freedom of Creation (2006). *Rapid Manufactured Textiles.* Accessed via: http://www.freedomofcreation.com/press-archive/FOC_RM_Textiles.pdf on 25/02/14.

Gibson, I., Rosen, D.W. and Stucker, B. (2010). *Additive Manufacturing Technologies.* Springer Science+Business Media, LLC 2010, Springer, New York.

Giloh, E. (2012). *Methods to produce stretchable products*. US patent US8323764 B2. Accessed via: http://www.google.com/patents/US8323764?dq=inassignee:tamicare+inassignee:ltd&source=uds on 13/03/14.

Goswami, B.C., Anandjiwala, R.D. and Hall, D.M. (2004). *Textile Sizing*. Marcel Dekker, Inc., U.S.A. ISBN: 0-8247-5053-5.

Hague, R. (2006). 'Unlocking the Design Potential of Rapid Manufacturing', in Hopkinson, N., Hague, R.J.M. and Dickens, P. (ed.) *Rapid Manufacturing,* John Wiley & Sons, Ltd., West Sussex, England.

Hardaker, C.H.M. and Fozzard, G.J.W. (1997). The bra design process – a study of professional practice. *International Journal of Clothing Science and Technology,* 9:4 (311-325).

Hopkinson, N.,and Dickens, P. (2006). 'Emerging Rapid Manufacturing Processes', in Hopkinson, N., Hague, R.J.M. and Dickens, P. (ed.) *Rapid Manufacturing,* John Wiley & Sons, Ltd., West Sussex, England.

i.materialise (2014). *Material Overview: Rubber-like* [Online] Materialise. Accessed via: http://i.materialise.com/materials/rubber-like on 27/03/14.

Kajiwara, K. (2009). 'Synthetic textile fibers: structure, characteristics and identification', in Houck, M.M. (2009). *Identification of textile fibers*. Woodhead Publishing Limited, Cambridge, England.

Karana, E., Barati, B. Rognoli, V. and Zeeuw van der Laan, A. (in review). *Material Driven Design (MDD): An Illustrative Case on Designing With Waste Coffee Grounds*.

Karana, E., Hekkert, P. and Kandachar, P. (2009). Sensorial properties of materials for creating expressive meanings. *Materials & Design,* Vol. 30, Issue 7 (2778-2784). Accessed via: http://www.sciencedirect.com/science/article/pii/S0261306908004883 on 17/03/14.

Karana, E., Hekkert, P., Kandachar, P. (2010). A tool for meaning driven materials selection. *Materials & Design,* Vol.31, Issue 6 (2932-2941). Accessed via: http://www.sciencedirect.com/science/article/pii/S0261306909007110, on 20/03/14.

Klemm, D., Heublein, B., Fink, H. and Bohn, A. (2005). Cellulose: Fascinating Biopolymer and Sustainable Raw Material. *Angewandte Chemie International Edition 44:22 (3358-3393).* Accessed via: http://onlinelibrary.wiley.com/doi/10.1002/anie.200460587/full, on 09/07/14.

Le Blan, T., Vouters, M., Magniez, C. and Normand, X. (2007). 'The Development of Non-Wovens' in Duquesne, S., Magniez, C. and Camino, G. (ed.) (2007).

Multifunctional Barriers for Flexible Structure, Springer Series in Material Science, Springer Berlin Heidelberg New York, p139-150.

Lewin, M. (ed.) (2007). *Handbook of Fiber Chemistry, third edition.* Taylor & Francis Group, Boca Raton.

Li, Y. (2010). The Science of Clothing Comfort. *Textile Progress,* 31:1-2, 1-135, DOI: Accessed via: http://www.tandfonline.com/doi/pdf/10.1080/00405160108688951 on 17/03/14.

Liao, C. and Lee, C. (2010). The application of codesign in new bra product innovations. *International Journal of Clothing Science and Technology,*22:2/3 (211-227).

Ljungberg, L.Y. (2005). Materials selection and design for development of sustainable products. *Materials and Design 28 (2007) 466-479.*

López Pradas, A. (2014). *Upcycle it yourself: design for do-it-yourself with industrial waste as a base.* Graduation Report, Industrial Design Engineering, TU Delft.

Material ConneXion (2014). *MC# 7081-01* [Online]. A Sandow Company. Accessed via: http://library.materialconnexion.com/ProductPage.aspx?MC=708101 on 13/03/14.

Mikkonen, J. Kivioja, S., Suonsilta, H., Myllymäki, R. and Vanhakartano, S. (2013b). Printed Material and Fabric. Nordic Design Research Conference 2013, Copenhagen-Malmö.

Mikkonen, J., Kivioja, S. and Myllymäki, R. (2013a). Exploring classifications of wearable 3D printed objects. *Proceedings* of the 1st International Conference on Digital Fashion, 16-18 May 2013, London, UK.

Mugge, R., Schoormans, J.P.L. and Schifferstein, H.N.J. (2009). Emotional binding with personalized products. *Journal of Engineering Design,* 20:5, 467-476.

Nervous System (2014). *Kinematics Bodice* [Online]. Nervous System Blog: Explorations in Generative Design and Natural Phenomena. Accessed via: http://n-e-r-v-o-u-s.com/blog/?p=4780, on 21/04/14.

O'Brien, H.L. and Toms, E.G. (2008). What is User Engagement? A Conceptual Framework for Defining User Engagement with Technology. *Journal of the American Society for Information Science and Technology* 59(6): 938-955. Accessed via: http://onlinelibrary.wiley.com/doi/10.1002/asi.20801/pdf, on 13/05/14.

OpenKnit (n.d.). *About* [Online]. OpenKnit: open source knitting. Accessed via: http://openknit.org/build/, on 21/04/14.

Oxman, N., Kayser, M., Laucks, J., Uribe, C.D.G. and Duro-Royo, J. (2013). *Silk Pavilion, 2013 CNC Deposited Silk & Silkworm Construction,* MIT Media Lab. Accessed via: http://matter.media.mit.edu/environments/details/silk-pavillion, on 21/04/14.

Patel, M. and Bhrambhatt, D. (n.d.). *Nonwoven Technology for Unconventional Fabrics.* DTT, Be in Textile Technology, M.S.University, Vadodara.

RepRap (2014). *Fused Filament Fabrication.* Accessed via: http://reprap.org/wiki/Fused_filament_fabrication, on 24/03/14.

Roozendaal, M.C. (2007). *Designing Engaging Interactions with Digital Products.* Dissertation, Eindhoven University of Technology, Department of Industrial Design.

Rosen, D.W. (2007). Computer-Aided Design for Additive Manufacturing of Cellular Structures. *Computer Aided Design & Applications,* Vol.4, No.5 (585-594).

Schrijnemakers, J.G.P.M. and Schulte, J.C.G. (1985). *Textielwarenkennis.* Wolters-Noordhoff bv Groningen, The Netherlands.

Smith, P. A. (2000). 'Technical Fabric Structures – 3. Nonwoven fabrics', in Horrocks, A.R. and Anand, S.C. (2000) *Handbook of Technical Textiles,* Woodhead Publishing Ltd, Cambridge.

Smithers Apex (2014). *Discussion: Fashion and Wearable Technology - Can they Work Together?* [Online] Smithers Apex. Accessed via: https://www.smithersapex.com/market-reports/discussion-fashion-and-wearable-technology-can-they-work-together.aspx, on 23/04/14.

Sondhelm, W.S. (2000). 'Technical Fabric Structures – 1. Woven fabrics', in Horrocks, A.R. and Anand, S.C. (2000) *Handbook of Technical Textiles,* Woodhead Publishing Ltd, Cambridge.

Telenko, C. and Seepersad, C.C. (2010). Assessing Energy Requirements and Material Flows of Selective Laser Sintering of Nylon Parts. 21st International Solid Freeform Fabrication Symposium, *Solid Freeform Fabrication Proceedings (289-297),* University of Texas, Austin. Accessed via: http://www.academia.edu/1002963/Assessing_Energy_Requirements_and_Material_Flows_of_Selective_Laser_Sintering_of_Nylon_Parts on 24/03/14.

Teunissen, J. (2013). The Next Thread. *CRISP Magazine #2 (3-7).*

The Economist (2012). *The third industrial revolution.* April 12st, 2012, The Economist Newspaper Limited. Accessed via: http://www.economist.com/node/21553017 on 13/07/14.

Tridico, S. R. (2009). 'Natural animal textile fibres: structure, characteristics and identification', in Houck, M.M. (2009). *Identification of textile fibers.* Woodhead Publishing Limited, Cambridge, England.

Van der Velden, N.M., Patel, M.K. and Vogtländer, J.G. (2014). LCA benchmarking study on textiles made of cotton, polyester, nylon, acryl or elastane. *The International Journal of Life Cycle Assessment* 19-2 (331-356).

Vogtländer, J. (2012). *LCA: a practical guide for students, designers and business managers.* Second Edition. VSSD, Delft, The Netherlands.

Wong, K.V. and Hernandez, A. (2012). A Review of Additive Manufacturing. *ISRN Mechanical Engineering,* vol.2012, article ID 208760. Accessed via: http://www.hindawi.com/journals/isrn.mechanical.engineering/2012/208760/cta/ on 25/03/14.

XYZ Workshop (2014). *Inbloom dress by XYZ Workshop at 3D printshow New York 2014* [Online] XYZ Workshop. Accessed via: http://www.xyzworkshop.com/inbloom/ on 27/03/14.

Zhuo, W.L., Sheng, C.D., Wei, Q. and Bin, L. (2011). Effects of elastic materials on pressure comfort of tight-fit bras. *Applied Mechanics and Materials Vol. 79 (221-226).* Accessed via: http://www.scientific.net/AMM.79.221, on 08/08/14.

APPENDICES

A. AM PROCESSES

	Name	Suitable Materials	Based on	Accuracy	0D/1D/2D	Time	Supports	Post-processing	Advantages	Limitations
Liquid-based processes		Photosensitive polymers							Superior accuracy and definition Similar to injection moulding	Poor material properties (→UV): mechanical and appearance over time Sensitivity to humidity
	Stereolithography		Uv	100µm	0D		automatically	Curing; removing supports		
	Jetting systems	Acrylate-based photopolymer	Uv	16 µm	1D		simultaneous	Removing supports	Resolution; speed	Material properties
	Direct Light Processing (DLP)	Acrylate-based photopolymer	Uv		2D	10-15s /layer			Small parts; speed	
	High-Viscosity Jetting	Powder-filled polymer paste	Small drops							
	MAPLE		Uv	1-10 µm						
Powder-Based Processes		Polymers; metals; ceramics							Material properties: mechanical; stability	
	Selective Laser Sintering (SLS)	Polymers*; metals; ceramics	Laser	100µm	0D		Unnecessary	For metals and ceramics: burning, sintering and infiltration		
	Direct Metal Laser Sintering	Metal	Laser							
	3D Printing	Metal	Jets		1D			burning, sintering and infiltration		Poor surface finish
	Fused Metal Deposition	Metal	Laser		0D	Slow				Poor surface finish
	Electron Beam Melting	Conductive materials/ surfaces	Electron beam		0D	High	Unnecessary			
	Selective Laser Melting	Metal	Laser							
	Selective Masking Sintering	Glass-filled nylon	Infrared		2D	10-20s layer				
	Selective Inhibition Sintering	Polymer	Jets with inhibitor		1D/2D				Reduced thermal gradient	
	Electrophotographic Layered Manufacturing		laser		1D			sintering		
	High-Speed Sintering	Nylon (with carbon-black)	Radiated energy						Variable sintering rates; mechanical properties	
Solid-Based Processes		Polymers; ceramics								
	Fused Deposition Modelling (FDM)	(thermoplastic) polymer	Nozzle	0.3mm	0D	Slow	simultaneous	unnecessary	Easy to set-up	
	Sheet Stacking	Paper; polymers; metals	Sheets					Removing unwanted material	More suitable for simple geometries	

[Hopkinson & Dickens, 2006]

*Semi-crystalline polymers give better mechanical properties than amorphous polymers

B. AALTO VISIT

Soft/Mesh is a fabric-like, 3D printed material developed by Olga Sjöroos and Jussi Mikkonen from Aalto University. It consists of printed hexagons in a hard material, embedded in a mesh of a flexible material. Because of this ongoing research into 3D printed textiles, Aalto was kind enough to invite us to come to their university to show us what they have been working on and to let us use their facilities for some experiments.

A quick summary of the trip as follows:

- Sunday 06/04: arrival and check-in at the hotel.
- Monday 07/04: First meeting with employees from research department, including a small presentation from our side regarding the contents of our graduation. The researchers explain their research subjects, which include user experience, prototyping and co-design. We are invited on a tour through the facilities of the faculty, including their extensive workshop rooms, while the first models are being printed.
- Tuesday 08/04: We arrive at the faculty early to transfer a new batch of models to the printer, after which the creative session starts at 9:30. There are 11 students from the course Interactive Prototyping who join the session that is facilitated by Cees Jan. The session lasts until 12:00. In the afternoon we discuss the results and work on some more models.
- Wednesday 09/04: We arrive early to print some more models, only to find that the printer will be occupied for the next few hours. Jussi offers to print them later and send them to us. We get another tour through the building, this time we visit the FabLab and some other facilities. Around 12:00 we leave to catch our plane.


FIGURE 66. WARM WATER JET

RESEARCH IN AALTO

Jussi explains that the research at Aalto is mostly focused on printing smart textiles. For this they have for instance developed a very flat type of battery and are experimenting with embroidering conductive thread.

They cooperate a lot with the fashion department on the floor below. Most of the students there are not familiar with 3D modelling, and therefore have a hard time including 3D printed parts in their designs. This is the main reason why their research is focused on creating flat structures at first, in order to allow the fashion students to understand and work with it. They are already encouraging the fashion students to create (small) designs using Adobe Illustrator, which can easily be translated to STL files.

EXPERIMENTS

The available 3D printer is a multi-material Objet Connex 350. This printer has 8 print heads, and is capable of printing different materials simultaneously. The materials that were available at Aalto were a rigid white material (Vero White) and a rubber-like black material (Tango Black). It is possible to create up to 17 different materials by

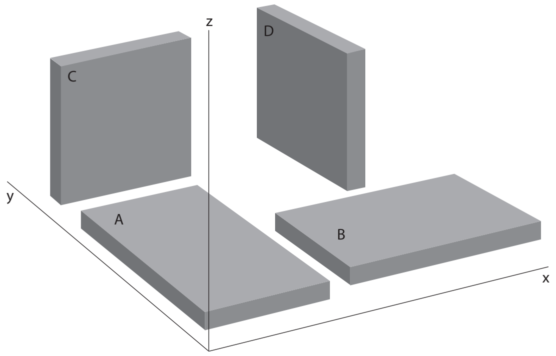


FIGURE 67. **PRINTING ORIENTATIONS**

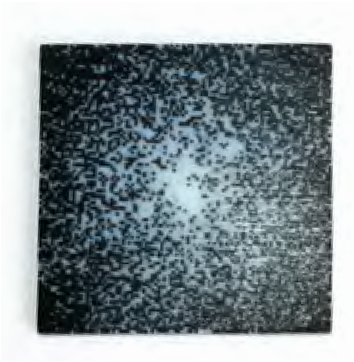


FIGURE 68. **SAMPLE 1**

FIGURE 69. **SAMPLE 2**

FIGURE 70. **SAMPLE 3**

mixing the two, resulting in a gray shade with varying hardness. The printer automatically adds support material that can be washed off with a warm water jet (Figure 66).

In order to assign different materials to different parts of a product, separate STL files need to be created. This was done by either using Solidworks to create separate parts, or by using a Grasshopper script in Rhino to create gradients.

A total of 7 models have been printed. Due to the specifics of the printing process, the printer is able to build the entire x,y plane in one movement. The z-height of the models mostly determines the duration of the process time, which is for a height of 10 mm approximately 2 hours.

The bottom side of the models is always matte, for the top surface a glossy or matte finish can be chosen. It has been shown that a glossy surface translates into a stronger material [Mikkonen et al., 2013b]. Furthermore, the material properties of the samples also depend on the printing direction. There are four orientations in printing direction (illustrated in Figure 67). Tests have shown that the A and B orientation is the most durable and has most uniform elongation (when applied to flat, fabric-like surfaces) [Mikkonen et al., 2013b]. Also, the orientation determines the surface characteristics of the samples; the A and B orientation result in a glossy, shiny surface, while the C and D orientation result in a "fuzzy", soft surface, that somewhat resembles suede or velvet.

All samples were printed in the A or B orientation, since this is much faster than the C or D orientation and requires less support material. The sizes of the samples were all 50 mm x 50 mm (x,y), except two with sizes 50 mm x 100 mm, with heights varying from 1 mm to 10 mm. They were designed to test several principles, for instance material gradients, controlled bending etc.

PRINTED RESULTS

The samples are shown in Figure 68 to Figure 74. All flat samples have a glossy top-surface. Since this surface is so smooth, the material is very sticky when it first comes out of the printer. The samples have a strange, sweet smell, which is quite obtrusive.

The boundaries where the two materials meet are most vulnerable to breakage. This can especially be seen in sample 4. The Tango Black material is quite weak and not tear-resistance, over time and due to repeated bending the material will break. It resembles rubber, although the response to bending is a little bit delayed, giving it a more 'obedient' feel.

Three variations on the gradient have been printed: one with Vero White in the center, one with Tango Black in the center, and one with a mixture of both in the center. The resolution of the gradient is too low to make it a visual gradient, therefore they seem pixelated.

FIGURE 71. **SAMPLE 4**

FIGURE 72. **SAMPLE 5**

FIGURE 73. **SAMPLE 6**

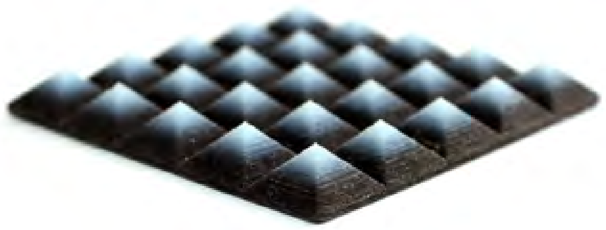


FIGURE 74. **SAMPLE 7**

Sample 1 can only be bend in the corners, due to the stiffness of the Vero White material. Sample 3 is much more flexible. The most interesting is sample 2, when bending this sample the center is most flexible, which is a counter-intuitive experience. This effect could be interesting to create flexible parts for joints etc.

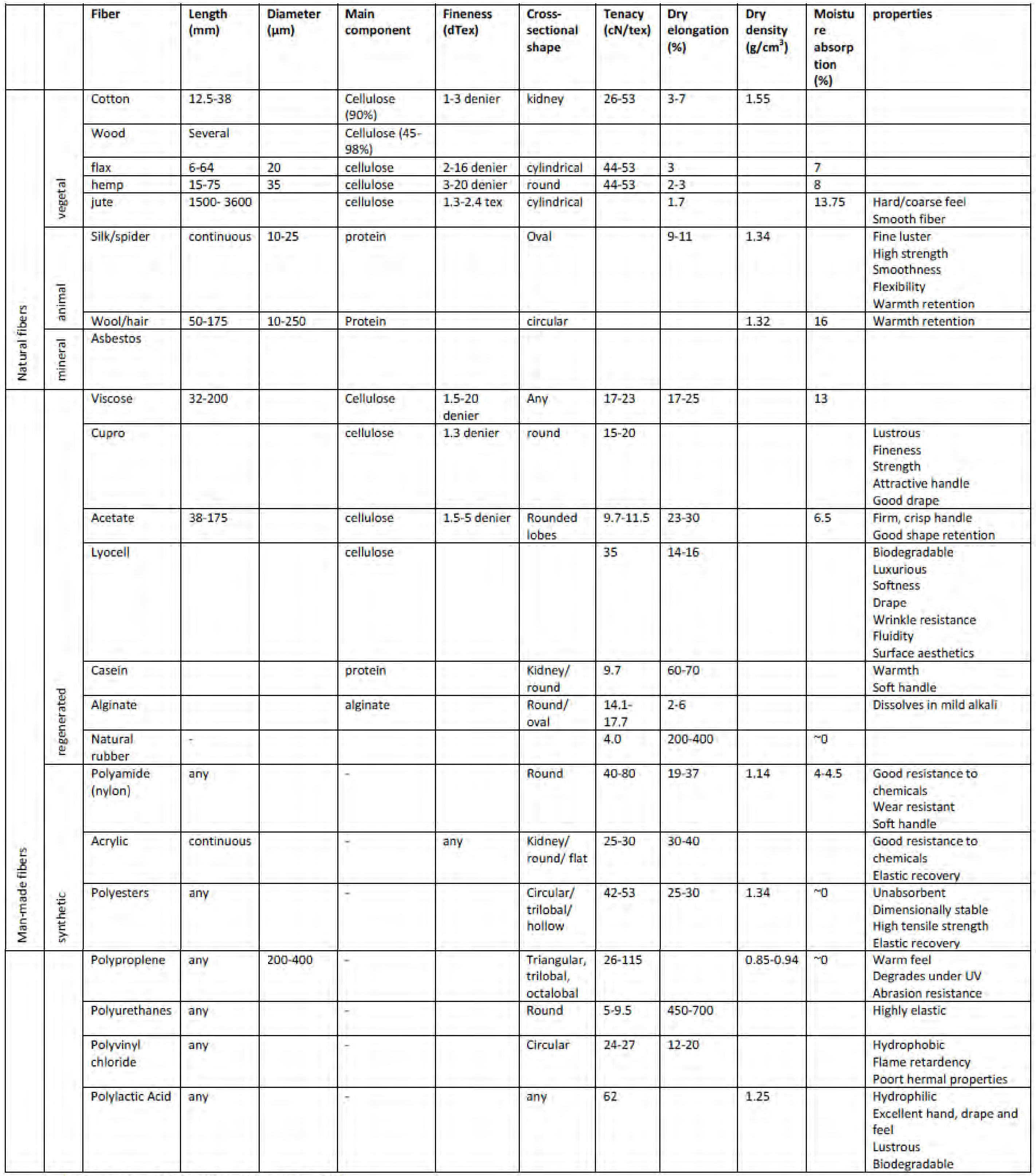
Sample 4 is very stiff due to the thickness of the material. However, it shows more flexibility orthogonal and diagonal to the direction of the stripes than parallel to them. This is an interesting effect that can be used to control bending behaviour. The sides of this sample also illustrate the different surface finishes that can be obtained in different orientations.

Sample 5 and 6 are both designed by projecting a bitmap image onto a shape. This creates a type of inner structure in the sample. The larger part of the sample consists of Tango Black, the rest is a mixture of black and white. The mixture is actually a little too flexible, although when bending the samples the internal structure shows itself. This creates interesting visual effects, but can also be used to control bending behaviour.

Finally, sample 7 shows an interesting combination of hard and flexible parts. The pyramids have been sliced in horizontal layers, and each layer has been assigned a material (mixture) with increasing hardness. The resulting pyramids are hardest on top, and actually quite sharp. The feeling of the sample has been described as 'crocodile skin'. The resulting material is still flexible, but also offers protection due to the hard parts.
There are a lot of opportunities of using a material that is naturally flexible to produce AM textiles. However, certain drawbacks of the material are its weakness and tearing behaviour; the fact that when printed smooth its surface is sticky and uncomfortable; and the fact that it is not permeable to air. This implies that even with a flexible material, a suitable design is necessary to create a comfortable garment.

C. FIBER PROPERTIES

The table on the next page shows the technical properties of a number of commonly used fibers. The fibers are divided into the categories: natural fibers (vegetal, animal, mineral) and man-made fibers (regenerated, synthetic).



		Fiber	Length (mm)	Diameter (µm)	Main component	Fineness (dTex)	Cross-sectional shape	Tenacy (cN/tex)	Dry elongation (%)	Dry density (g/cm³)	Moisture absorption (%)	properties
Natural fibers	vegetal	Cotton	12.5-38		Cellulose (90%)	1-3 denier	kidney	26-53	3-7	1.55		
		Wood	Several		Cellulose (45-98%)							
		flax	6-64	20	cellulose	2-16 denier	cylindrical	44-53	3		7	
		hemp	15-75	35	cellulose	3-20 denier	round	44-53	2-3		8	
		jute	1500- 3600		cellulose	1.3-2.4 tex	cylindrical		1.7		13.75	Hard/coarse feel Smooth fiber
	animal	Silk/spider	continuous	10-25	protein		Oval		9-11	1.34		Fine luster High strength Smoothness Flexibility Warmth retention
		Wool/hair	50-175	10-250	Protein		circular			1.32	16	Warmth retention
	mineral	Asbestos										
Man-made fibers	regenerated	Viscose	32-200		Cellulose	1.5-20 denier	Any	17-23	17-25		13	
		Cupro			cellulose	1.3 denier	round	15-20				Lustrous Fineness Strength Attractive handle Good drape
		Acetate	38-175		cellulose	1.5-5 denier	Rounded lobes	9.7-11.5	23-30		6.5	Firm, crisp handle Good shape retention
		Lyocell			cellulose			35	14-16			Biodegradable Luxurious Softness Drape Wrinkle resistance Fluidity Surface aesthetics
		Casein			protein		Kidney/ round	9.7	60-70			Warmth Soft handle
		Alginate			alginate		Round/ oval	14.1-17.7	2-6			Dissolves in mild alkali
		Natural rubber	-					4.0	200-400		~0	
	synthetic	Polyamide (nylon)	any		-		Round	40-80	19-37	1.14	4-4.5	Good resistance to chemicals Wear resistant Soft handle
		Acrylic	continuous		-	any	Kidney/ round/ flat	25-30	30-40			Good resistance to chemicals Elastic recovery
		Polyesters	any		-		Circular/ trilobal/ hollow	42-53	25-30	1.34	~0	Unabsorbent Dimensionally stable High tensile strength Elastic recovery
		Polyproplene	any	200-400	-		Triangular, trilobal, octalobal	26-115		0.85-0.94	~0	Warm feel Degrades under UV Abrasion resistance
		Polyurethanes	any		-		Round	5-9.5	450-700			Highly elastic
		Polyvinyl chloride	any		-		Circular	24-27	12-20			Hydrophobic Flame retardency Poort hermal properties
		Polylactic Acid	any		-		any	62		1.25		Hydrophilic Excellent hand, drape and feel Lustrous Biodegradable

[Le Blan et al., 2007; Goswami, 2004; Lewin, 2007]

D. LIFE CYCLE ANALYSES

This appendix gives additional information regarding the two life cycle analyses that have been conducted.

D1. LCA1

EXPLANATION OF ASSUMPTIONS

Scenario 1
Input material is 1,2 kg virgin PA2200 (the recycling of powder is left out of this LCA since this happens within the system), for lack of data on this specific material the value for PA6 was taken.

There is no eco-cost data on powder processing, SLS or industrial tumbling (yet). Therefore the necessary amount of energy was taken from literature [Telenko, 2010] and calculated to eco-costs (eco-costs of electricity = 26,27 €/GJ, [http://ecocostsvalue.com/EVR/model/theory/subject/2-eco-costs.html]). The waste from production is incinerated.

The average transport distance is assumed to be 75 km by truck. This is based on the following data. The office of Freedom of Creation is located in Amsterdam, where the textile is produced. It is assumed that shipments will be handled by the Dutch postal system, which uses trucks. It is also assumed that most of the deliveries will be delivered in the Randstad, in which the maximum distance to be transported is 75 km (distance between Amsterdam and Rotterdam). This distance is taken as an average to correct for shipments outside the Randstad (since the longest distance to be travelled in the Netherlands is 212 km, the distance from Amsterdam to Maastricht).

The recycling of nylon is not (yet) economically viable, therefore the product ends up in municipal waste and is incinerated for electricity, as is common in The Netherlands.

Scenario 2
Input material is assumed to be 0,5 kg viscose fibers and 0,5 kg natural rubber. It is unknown what material is used as wetting agent, but it is assumed to be less than 1% relevant and is therefore left out of the LCA.

Since there has been no detailed data available on the necessary energy for the production process, the value for powder coating has been chosen as similar process. The value is given per m2; it is therefore necessary to calculate the corresponding number of m2 per kilogram of material. It is assumed that one product has a surface of 0,24 m2 and a weight of 30 g. Therefore, 1 kg of material corresponds to 33,3 products. Each product is produced by means of 4 layers, which equals 0,96 m2 per product and therefore a total of 32 m2.

The manufacturing line is located next to the Tamicare headquarters, in Heywood, UK. It is assumed that the product is transported to the Manchester airport (44,4 km) by truck and then transported by aircraft to Schiphol, The Netherlands. In The Netherlands the average distance is again assumed to be 75 km.

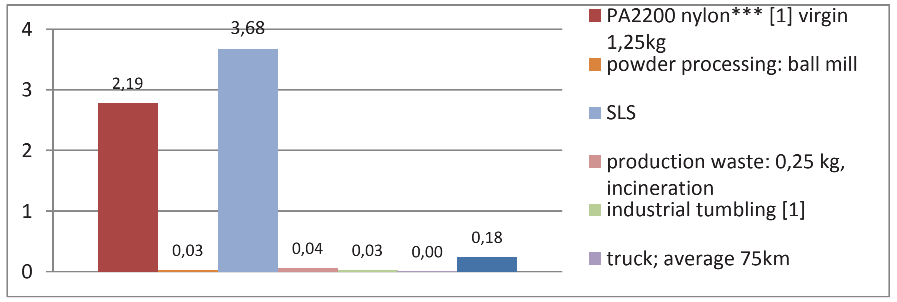
The use phase is not taken into account, since washing and drying of the fabric is unlikely, because the product is disposable.

The product is not recycled because it is a disposable product and no collection system is in place. Therefore, it ends up in municipal waste and is incinerated for electricity, as is common in The Netherlands.

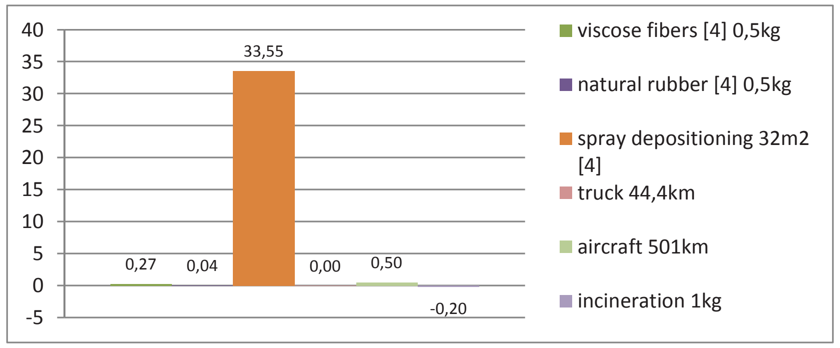
CALCULATIONS

The next page shows the detailed calculations that have been performed in order to determine the eco-costs for sc. 1 and sc. 2. The values for the eco-costs have been obtained from Idemat (2014), unless indicated otherwise. The second column for each calculation shows the number referring to the used data from Idemat. These data can be accessed via www.ecocostsvalue.com.

Scenario 1	number		Total Eco-costs (€) [2]	Energy use[3]
Materials				
	A.130.04.104	PA2200 nylon*** [1] virgin 1,25kg	2,78	
Production				
		powder processing: ball mill	0,03	1MJ*
		SLS	3,68	52-140MJ**
	F.090.01.104	production waste: 0,25 kg, incineration	0,06	
Finish		industrial tumbling [1]	0,03	1MJ*
Transport	C.010.06.103	truck; average 75km	0,00	
End-of-life	F.090.01.104	end-of-life incineration 1kg	0,23	
Total			€ 6,81	



Scenario 2			
Materials			
	A.140.01.115	viscose fibers [4] 0,5kg	0,27
	A.130.03.105	natural rubber [4] 0,5kg	0,04
Production			
	D.070.01.110	spray depositioning 32m2 [4]	33,55
Transport	C.010.06.103	truck 44,4km	0,00
	C.010.01.101	aircraft 501km	0,50
	C.010.06.103	truck; average 75km	0,00
end-of-life	F.070.01.104	incineration 1kg	-0,20
	F.090.01.102		
Total			€ 34,16



All values are obtained from Idemat 2014 data (accessed through http://ecocostsvalue.com/) , unless indicated otherwise.
*This value is based on the production of metal powder, since there is no data available on nylon powder production.
**This value depends on build density and height, in this case it can be assumed that the complex geometry would increase energy
*** Average build density is 30%; to produce 1kg of product 3,5kg of powder is required.
~ the wetting agent can be water, a surfactant solution or a hydrogel [6]

[1] http://www.freedomofcreation.com/press-archive/FOC_RM_Textiles.pdf
[2] eco-costs 2012 LCA data on products and services via http://ecocostsvalue.com/
[3] Telenko (2010)
[4] http://library.materialconnexion.com/ProductPage.aspx?MC=708101
[5] http://ecocostsvalue.com/EVR/model/theory/subject/2-eco-costs.html
[6] http://www.google.com/patents/US8323764?dq=inassignee:tamicare+inassignee:ltd&source=uds

D2. LCA 2

FDM ENERGY REQUIREMENTS

Since no data were available on the energy requirements of the FDM process, some measurements were performed using a kWh-measure. The results are presented in Table 09.

In order to calculate the required GJ for 1 kg of textile, the following calculations were done:

- calculating the average amount of material (g) printed per minute, based on the values measured from the prototype;
- calculating the average printing time for 1 kg of textiles (min);
- calcualting the average amount of energy required for preheating (MJ);
- calculating the average amount of energy required for printing (MJ);
- calculating the total energy usage to produce 1 kg of textiles by adding the average preheating energy to the average printing energy;
- and finally calculating the eco-costs by multipling the amount of GJ by 26,27 euro [www.ecocostvalue.com].

These calculations are shown in Table 08.

CALCULATIONS

The next page shows the detailed calculations that have been performed in order to determine the eco-costs. The values for the eco-costs have been obtained from Idemat (2014), unless indicated otherwise. The second column for each calculation shows the number referring to the used data from Idemat. These data can be accessed via www.ecocostvalue.com.

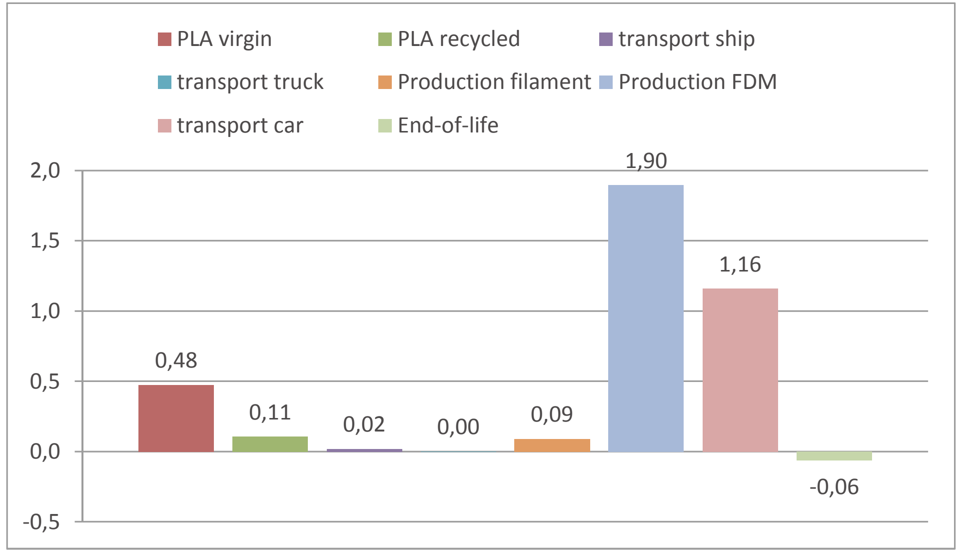
printing (g/min)		
	piece 1	0,061111111
	piece 2	0,076190476
	piece 3	0,085714286
	piece 4	0,083333333
	piece 5	0,075
	piece 6	0,115789474
	piece 7	0,091666667
	piece 8	0,100529101
	piece 9	0,094444444
	piece 10	0,091666667
	piece 11	0,111111111
	piece 12	0,093567251
	piece 13	0,113333333
	piece 14	0,078341014
average g/min.		0,090842733
printing time for 1kg (min)		11008,03512
energy usage preheat (MJ)		
	measurement 1	0,0378
	measurement 2	0,05652
	average	0,04716
energy usage printing (MJ/min)		
	measurement 1	0,005221053
	measurement 2	0,006717692
	measurement 3	0,006646316
	measurement 4	0,00763619
	measurement 5	0,006798525
	average	0,006555313
energy usage total (MJ/kg)		72,20827354
eco-costs (€/kg)		1,896911346

TABLE 08. CALCULATION OF ECO-COSTS FOR FDM PROCESS

	Preheat1	**Preheat2**	**Printing 1**	**Printing 2**	**Printing 3**	**Printing 4**	**Printing 5**	**standby**	**mat. change**	**level buildplate**
Nozzle T	220	220	220	220	220	220	220	20	210	-
Build plate T	60	75	60	75	75	75	75	20	-	-
Time	0:03	0:05	2:51	2:36	2:51	3:09	3:37	0:08	0:02	0:02
kWh	0,0105	0,0157	0,248	0,2911	0,3157	0,4009	0,4098	0,0007	0,0193	0,0015
V_{max}	228,2	228,2	229,6	228,3	226,5	230,5	229,1	226,2	229	226,6
V_{min}	227,1	225,2	225,9	224,4	223,9	223,8	225,8	225,3	225	225,8
A_{max}	1,004	0,97	0,796	0,968	0,922	0,933	0,941	0,164	0,97	0,344
A_{min}	0,285	0,152	0,153	0,155	0,153	0,148	0,155	0,153	0,152	0,203
W_{max}	213,7	205,6	148,1	203,3	188,4	195	197,2	5,2	205,6	44,9
W_{min}	26,5	3,7	3,7	4	3,9	3,5	4	3,9	3,7	13,4

TABLE 09. MEASURED ENERGY FOR FDM PROCESS

Scenario 1	number		Total Eco-costs (€) [1]	Energy use (GJ)[2
Materials				
	A.130.01.103	PLA virgin 0,5 kg	0,48	
	A.130.02.113	PLA recycled 0,5 kg	0,11	
Transport				
	C.070.01.104	boat 10.000 km 0,5 kg	0,02	
	C.010.06.103	truck 75 km 0,5 kg	0,00	
Production				
	D.120.01.103	Polymer extrusion	0,09	
		Fused Deposition Modelling	1,90	0,072208274
Transport				
	C.060.02.102	Passenger car 15 km	1,16	
End-of-life				
	F.090.01.110	incineration 0.5kg	-0,06	
Total			€ 3,69	



All values are obtained from Idemat 2014 data (accessed through http://ecocostsvalue.com/) , unless indicated otherwis

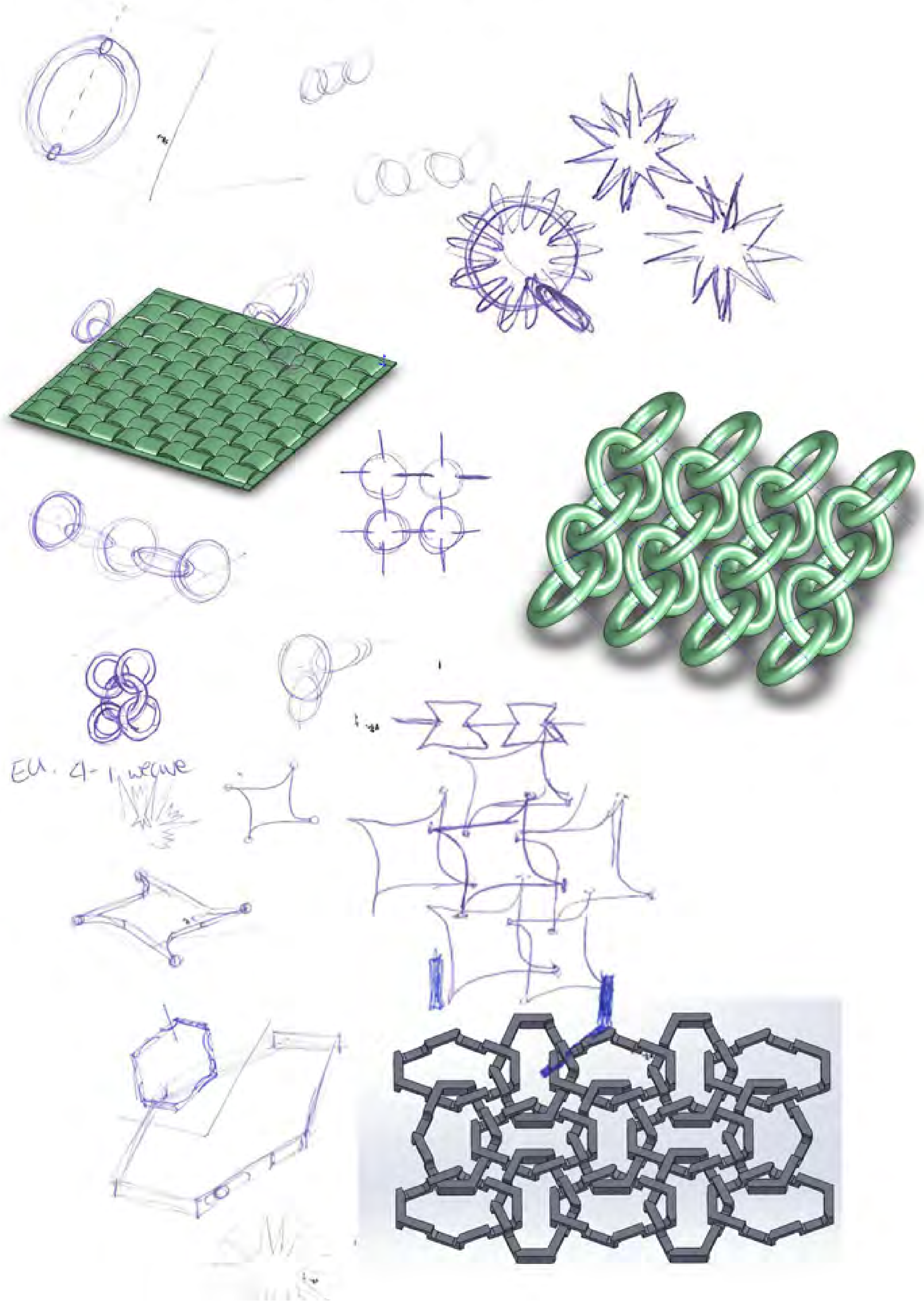
[1] eco-costs 2014 LCA data on products and services via http://ecocostsvalue.com/

[2] http://ecocostsvalue.com/EVR/model/theory/subject/2-eco-costs.html

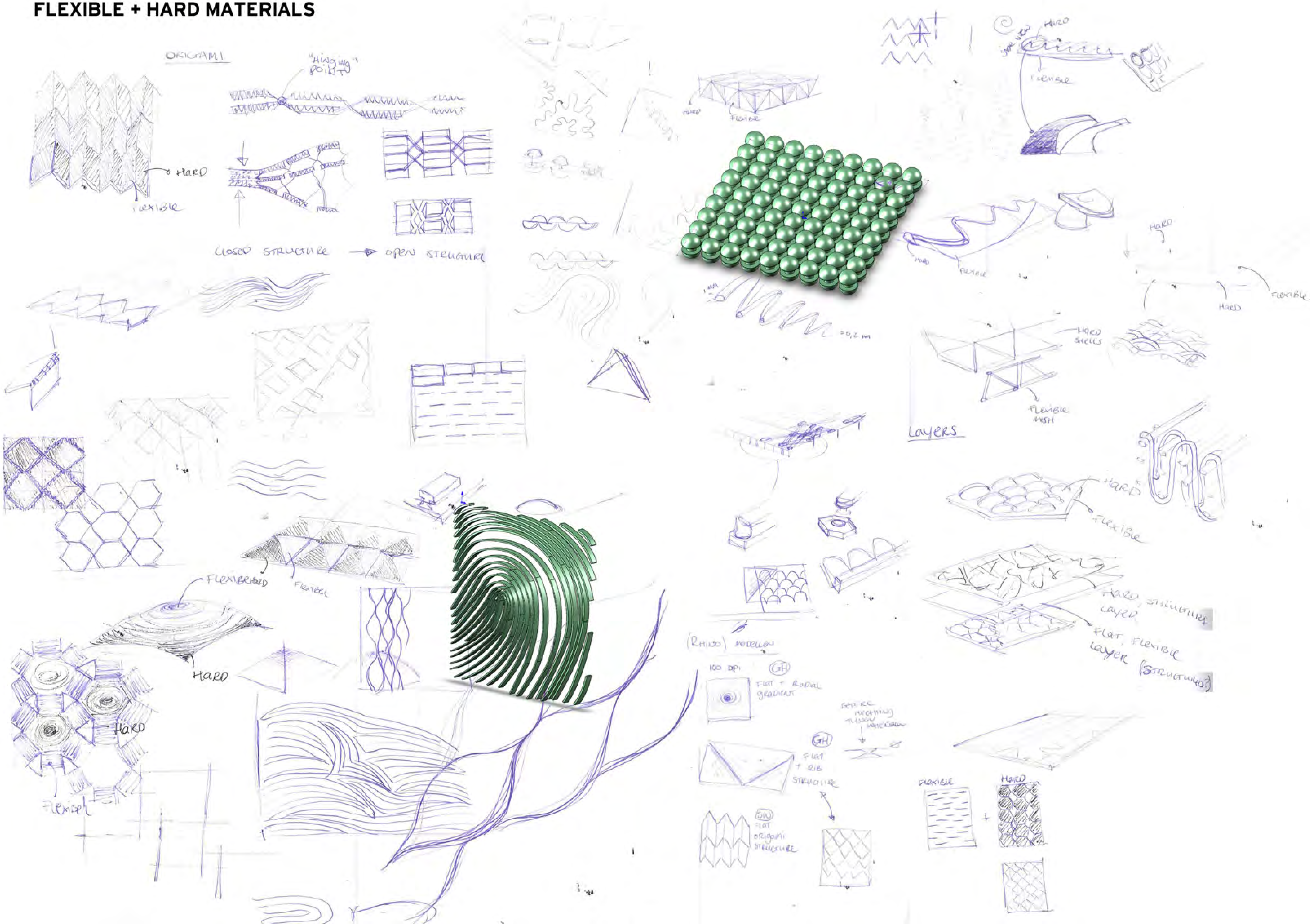
E. SAMPLES-IDEATION

This appendix will show on the following pages a number of sketches, models and ideas for the creation of 3D printed textiles that have been produced during the course of the project. Not all of them have actually been created as samples. They are divided into the three categories of 3D printed textiles: multipe assemblies, flexible (+ rigid) materials and thin structures.

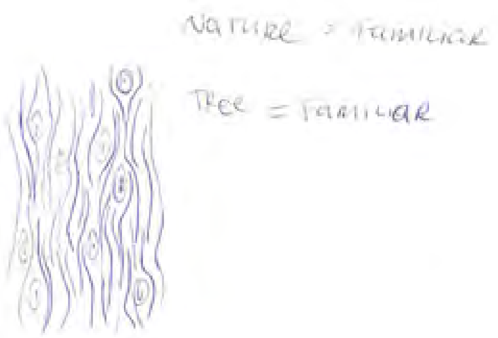
MULTIPLE ASSEMBLIES

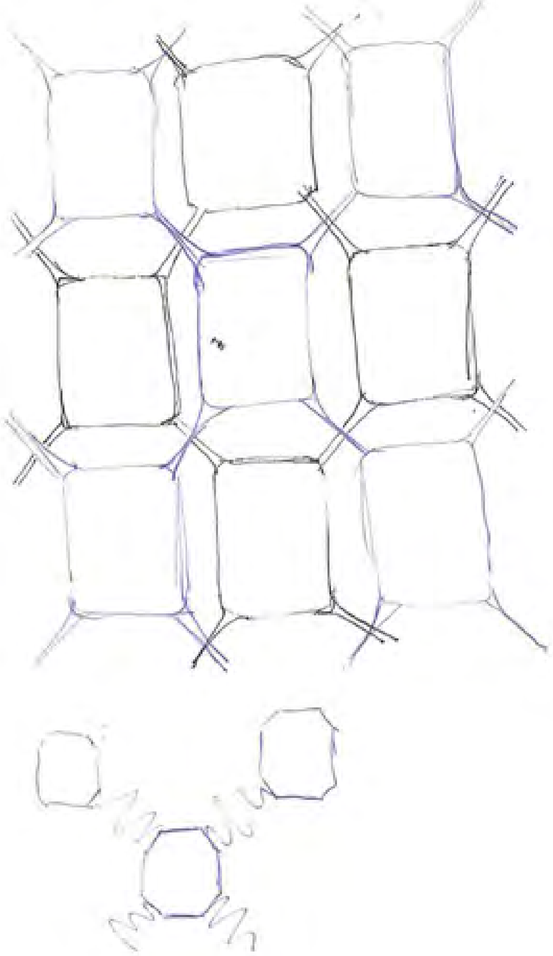


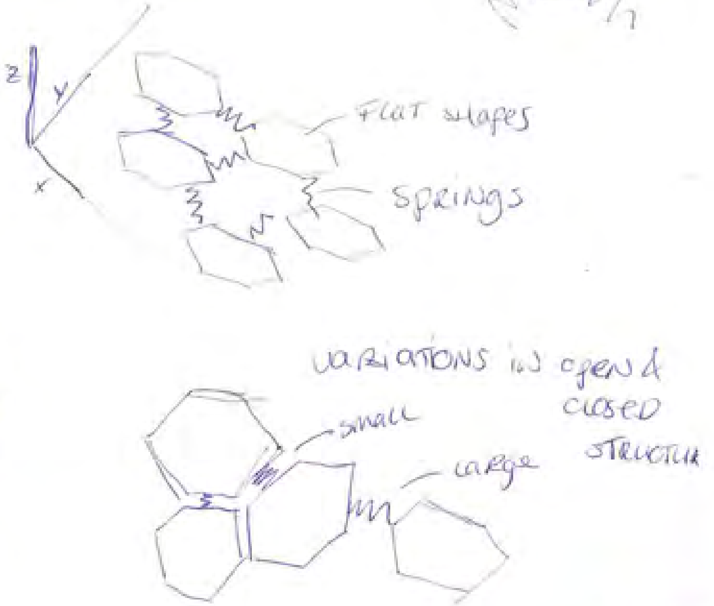
FLEXIBLE + HARD MATERIALS

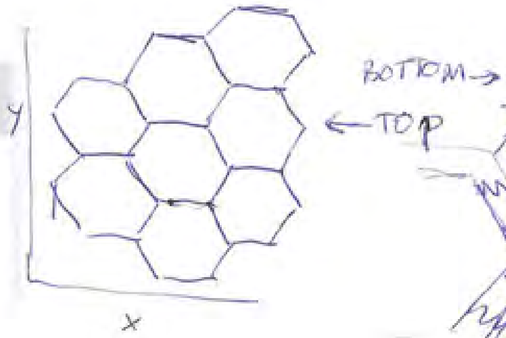


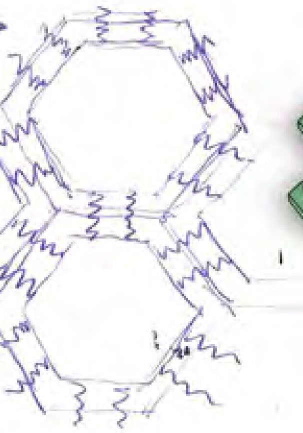
THIN STRUCTURES

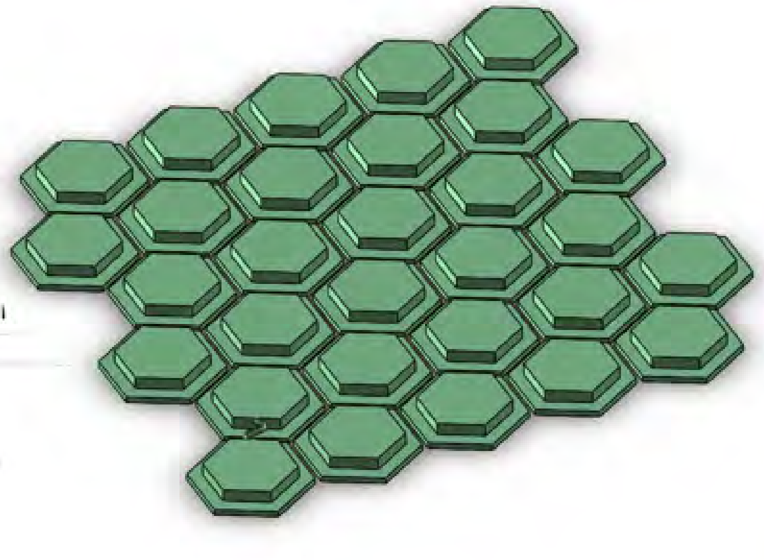


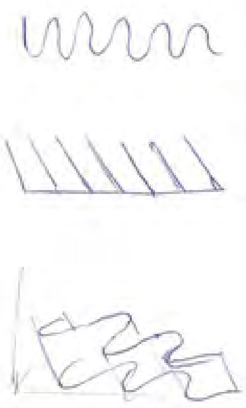








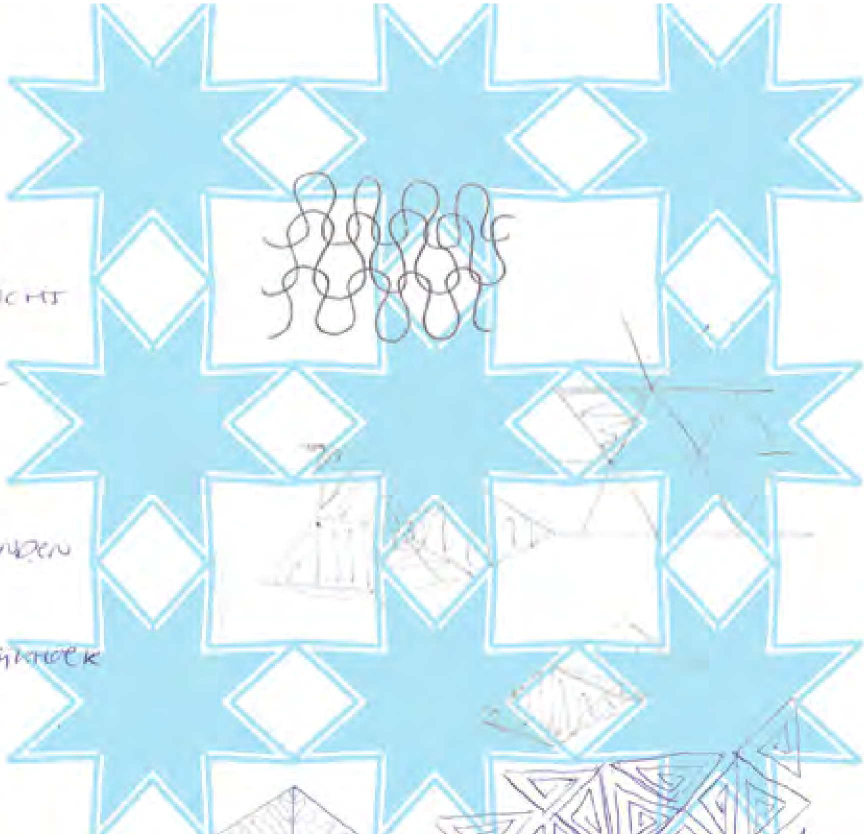


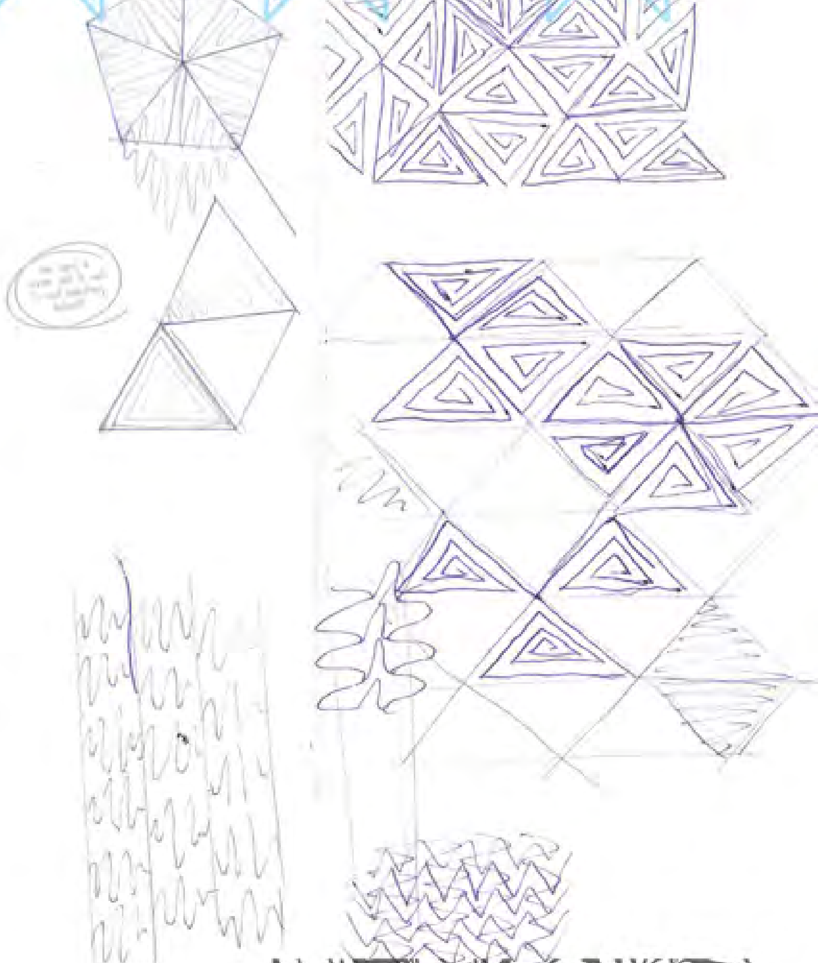


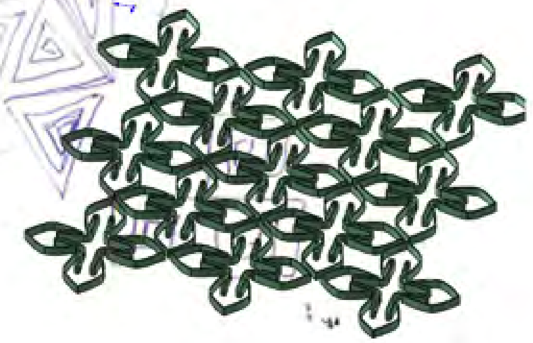
⇒ STRUCTUUR BUITENAANZICHT

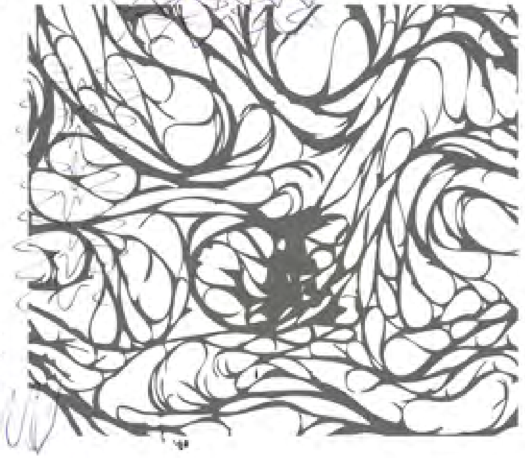
⇒ ZIJAANZICHT

⇒ SCHUINE WANDEN VEROORZAKEN OPEN/DICHTE LIJNWERK









F. CONTEXT PRINCIPLES

This appendix gives an overview of the list of context principles that were used for the creation of the vision. They were not adapted directly to the vision, which is why they have not been included in the main report, however they do sketch an overview of the relevant factors and developments in the context, from which the two main themes discussed in the report were derived. The context factors are divided into sections: economic, behavioral, sociological, commercial, technological, cultural, ergonomical, and sustainable.

ECONOMIC

1. There is a demand for cheap products, dictated by fast design.
2. Due to the economic recession, there is an increased market for second-hand goods.
3. There is a slow shift in consumerism from buying a product to leasing a product; at the end of its lifespan, the product is returned to the manufacturer.
4. Stores are beginning to increasingly offer digital manufacturing as a service.
5. There is a change in ownership of designs; more people and companies choose to spread their designs on the internet free of charge, for people that want to make or adjust it.
6. There is an increase in people and places that offer use of their production methods (Such as FabLab).
7. In the UK, it is obligatory for schools to have a 3D printer for educational purposes.

BEHAVIORAL

8. Meanings people attribute to products are often linked to memories of people or situations.
9. People tend to take more care of products if they mean more to them (being willing to repair them).
10. Not everybody has a desire to design their own products.
11. The maker movement increases value in products, since they are tailor made to the exact wishes of the maker.
12. Memories and experiences are what make a person unique.
13. Fashion is one of the most personal and direct ways to express oneself.
14. The right kind of clothing can give people confidence.
15. The attitude towards clothing is very different for men and women.
16. People want to be unique, but at the same time have a sense of belonging.
17. Even though synthetic materials can have superior properties, natural materials are often preferred due a more pure, luxurious image. [Ljungberg, L.Y, 2005].
18. "The law of conservation of energy tells us we can't get something for nothing – yet we refuse to believe it." Isaac Asimov
19. Homemade gifts are more personal.
20. The hype of (desktop) 3D printing is causing people to create more 'useless' things, such as plastic statues, just because they can make it themselves.
21. People like to feel protected.
22. If clothing is comfortable it is unobtrusive, if it is not comfortable it will be a source of annoyance.
23. Products that have no meaning to people are easily disposed of.
24. Some materials are perceived as more meaningful as they mature, such as leather and wood, because they become more personal to people.
25. Repetition leads to adoption, which eventually can lead to boredom.
26. New things are exciting.

SOCIOLOGICAL

27. The Throwaway Society describes the problematic development in today's society of a "use, wear and throw-away"—attitude towards products. Fashion and trends in society attribute to this problem.
28. There is an increasing demand for fair and honest products and more transparency in production processes.
29. Idols can be very influential of acceptance of certain trends.
30. The phenomenon 'fashion' has more to do with lifestyle than with products.
31. Synthetic polymers often have a negative image of being cheap and of inferior quality than natural materials.
32. Fashion is imitative by nature, although it is used to express the uniqueness of people.
33. 3D printing is perceived as an innovative, almost 'magic-like' production method, therefore products made by 3D printing should not look boring or plain, since this is often a disappointment to people.
34. Humans have a need of spectacularity; superficiality and spectacularity are genuine qualities, whether we like it or not. – Alessandro Baricco

COMMERCIAL

35. In the fashion world, there is little attention for the design and construction of PSS [Teunissen, 2013].
36. "In the fashion industry, a product has to look impressive before many consumers will even consider wearing it." [Smithers Apex, 2014]
37. 3D printing brings customization and personalization closer to home.
38. There are always market trends that make certain types of materials popular in a certain period, after which they may be replaced for other types of materials that have become more fashionable or better suited for the use [Ljungberg, L.Y, 2005].

TECHNOLOGICAL

39. Research into new, biological materials that can be 3D printed is ongoing (such as cellulose).
40. There is a desire to create cradle-to-cradle scenarios for desktop 3D printing.
41. There is a need for more advanced 3D modelling programs, to fully optimize the possibilities of additive manufacturing.
42. There is a need for simplified 3D modelling programs that allow consumers to create their own 3D products to print.
43. People do not know how the programmer of 3D modelling programs meant for people to make things; there are always several ways to model something.
44. Biomimicry is becoming a more meaningful process because of the possibilities of additive manufacturing to mimic the way nature builds things.
45. Additive manufacturing offers unique opportunities to integrate smart technology into clothing.
46. 4D printing is defined as a 3D printed object that changes shape or self-assembles over time; naturally embedding smartness in materials.
47. Adobe Photoshop has recently launched a plug-in for 3D printing.
48. 3D printing is a low-tech way of bringing technology to not so tech-savvy people.
49. There is an increase in the number of (mixed) materials that is used for one product (complex products) [Ljungberg, L.Y, 2005].
50. 3D printed textiles are classified as smart textiles or wearable technology.
51. Writing code is becoming the new craftsmanship.

CULTURAL

52. Meanings depend on cultural values, as well as personal associations.
53. Many young girls describe themselves as 'fashionista's' and 'addicted to fashion' as a means of status, which paves the way for fast design.
54. As an opposite reaction, slow design is increasing in popularity, which pleas to improve the lifespan of products by repairing and maintaining them and making them a timeless design (not susceptible to fashion).
55. Customization of products meets people's needs in a more effective manner, thus increasing the likeliness of longevity.
56. Cultural aspects and tradition determine the attitude people have towards certain materials [Ljungberg, L.Y, 2005].
57. Craftsmanship is an important attribute of fashion.
58. Perfect products are boring: designers like to make use of the imperfections of certain production processes to give expression to their products.
59. The maker movement is a global trend of people encouraging each other to make and design their own products, rather than buying general products.
60. Desktop 3D printers are currently a hype for DIY-ers.
61. Shared economy is the trend in which access is valued over ownership. Open design is the response to this from a design perspective, in terms of collaborative creation and free sharing of designs.

ERGONOMICAL

62. The human body is active, dynamic, diverse and changing.
63. The human body can be seen as a support environment for clothing.
64. For clothing to be unobtrusive, it must be worn close to the body, so the brain sees it as an extension of the body.
65. Due to confection, basically everybody wears the wrong size of clothing.
66. The feeling of fabrics is very important in clothing.
67. Smart wearables rarely make it to the general public, because they are not sufficiently tested throughout the production chain: aesthetics, technology, comfort, wearability and performance are not sufficiently integrated [Click NL, 2014].
68. Clothing can be considered a system interacting with the body.

SUSTAINABLE

69. 3D printing is often misperceived as being a more sustainable production method.
70. Biological materials are not necessarily more sustainable than other materials.
71. In order for materials to be recycled, they have to separable from each other, therefore mixtures of materials are undesirable.
72. People have little understanding of the factors that attribute to sustainable products.
73. People are easily fooled into thinking something is sustainable, by using words such as 'natural' or 'biological'.
74. Awareness of the necessity of using more sustainable resources is increasing; and people want to contribute to this by buying the right products.
75. People like to take care of products that have meaning to them by taking care of the material or making small repairs.
76. People are more willing to make sustainable choices if there is a financial advantage for them.
77. A way to make products score better on a sustainable scale is by increasing the use time.
78. The sustainability of clothing can be largely influenced by the use phase; if people wash the product often with a non-energy efficient washing machine, the environmental impact increases rapidly.
79. The current garment industry is unsustainable on multiple levels, which is why there is an opportunity for 3D printing to reshape this industry.
80. Sustainable development can be divided in Environment, Equity and Futurity [Ljungberg, L.Y, 2005].
81. Life Cycle Assessment (LCA) is a useful tool to help understand the environmental impact of a product [Ljungberg, L.Y, 2005].
82. According to design for sustainability, it is important not to use material mixtures that cannot be separated, since these are harder (or impossible) to recycle.

G. MEANING DRIVEN MATERIAL SELECTION

INTRODUCTION

The Meaning Driven Material Selection (MDMS) method was developed by Karana (2009) as an approach to explore the relationship between materials and meanings and to translate these into tangible material properties. In this method, a number of participants are asked to select a material that fits a specific meaning and answer a number of questions regarding this material. By analysing the response of the participants both qualitatively and quantitatively, the designer can get an idea as to what technical and sensorial properties attribute to that particular meaning. The results can be visualized in a Meanings of Materials (MoM) model, which incorporates the interactions between user, material and product. More on the MDMS method can be found in Karana (2009).

METHOD

Two MDMS studies were conducted at the same time, one for the meaning intriguing and one for the meaning familiar. The participants were all industrial designers or students of industrial design. They were asked to fill in the following questions by means of an online survey:

- to select a material that fits the given meaning;
- to upload one image of the material itself, and one of the material embodied in a product;
- to explain in their own words why they thought this material fit the meaning;
- to rate the material on a number of sensorial properties (see next section).

DETERMINING THE SENSORIAL PROPERTIES

The decision was made to let people pick the material freely, without limiting them to textiles. This was decided for a number of reasons, most importantly to prevent people from basing their choice mostly on the appearance of the textile (for example, it was anticipated that for the meaning intriguing people would choose an intriguing pattern, rather than that the properties of the textile where perceived as intriguing). Therefore, the comfort properties of textiles that where determined in chapter 5.5, could not directly be applied as sensorial properties in the research.

The sensorial properties that were determined by Karana (2010) as relevant for use in Meaning Driven Material Selection are softness, weight, ductility, elasticity, strength, elasticity, roughness, warmth, reflectiveness, glossiness and transparency.

However, it is important that the sensorial properties that are used can be translated to textile-like materials. Therefore, some of the properties where left out, that either could not be translated to textile-like materials or were not relevant for textile-like materials; such as reflectiveness, ductility and strength.

Strength is of course relevant for textiles/clothing as well, but this is more a general requirement for clothing: namely that it should withstand forces and friction caused by the human body during wear. Since it is not useful to produce clothing that is less strong than required for use, this property was left out of the sensory properties. Also, strength is not a property used to describe textiles.

Softness has a different meaning for textiles than in general. For textiles, it can be expressed in compression, flexibility and smoothness of the fabric [Li, 2010].

Compression is related to the thickness of the textile and its tendency to deform under pressure. Flexibility relates to the suppleness of the fabric and the manner in which it drapes [Li, 2010]. Smoothness describes the feeling of the surface layer of the fabric, with an absence of rough or scratchy parts. For materials in general, softness can be described as the tendency of the material to give in to pressure, and is therefore equal to compression. Therefore, the choice was made to include compressibility instead of softness, although the extremes are the same (hard-soft). Together with roughness and flexibility, this can be used to describe the softness of the fabric, and is therefore not used as a property on its own.

Some of the identified comfort properties were still found important to use in the sensorial properties scale, although some have been reformulated to make them more general. Absorbance was reformulated to dryness with absorbent and clammy as extremes; drapability was reformulated to flexibility, with stiff and flexible as extremes.

To test whether the properties were applicable and relevant to describe all types of materials, and not just textiles, a small number of participants was asked to fill in the properties for a simple plastic product (a phone cover). Afterwards, they were asked what properties they found hardest to fill in and why. Because of the responses of these participants, the properties coarseness (coarse – fine) and naturalness (natural – synthetic) were removed from the list. For coarseness because the participants connected this with the age of the material and whether it looked used, which was not the intended meaning. Naturalness was removed because the participants had good knowledge on materials and (with good reason) remarked that it was either natural or not, nothing in between. The rest of the properties were kept, since they did not pose any problems when filling in.
All properties of the list are described below, including their (anticipated) relevance to textile-like materials.

Roughness
Refers to the surface of the material, the extremes are rough and smooth.

Weight
Describes whether the perception of the material is heavy or light.

Elasticity
Describes whether the material is elastic or not elastic.

Warmth
Describes whether the material is perceived as warm or cool; for instance glass could be considered cool, while plastics may be considered warm.

Glossiness
Describes the glossiness of the material: a glossy material can be considered lustrous, and a matte material is considered dull. Translated to fabrics, this refers to the overall appearance of the material (for instance, silk is known for its lustre, while wool is dull).

Transparency
It was anticipated that transparency might be a relevant property for the meaning intriguing. It can be transferred to textiles by the amount of cover provided, rather than by the transparency of the actual base material: a coarse, open structure can be considered transparent, while a fine, dense structure can be considered opaque.

Dryness
This refers to the permeability of the material to water, and is related to the density. A porous material will be more permeable to water, and will thus feel dryer. A dense material will not be easily penetrated by water, therefore the water will remain on the surface of the material and make it feel clammy. Untreated wood is an example of a dry material, plastic is an example of a clammy material.

Flexibility
The tendency of a material to bend under stress. For textiles, the flexibility determines the drapability of the fabric as well; a thin, light material is more flexible and drapes better, a thick, stiff material can still be flexible but does not drape as well.

Toughness
For textiles, the coarseness of the material was found to be very relevant [Li, 2010]. However, it is hard to apply this to other material (groups), since it is more related to the application of the material than the other properties described. However, since for textiles the material and structure are intertwined, it was decided to include this property in the list. Its extremes are tough and delicate, which are chosen because they are more generally applicable than coarse and fine.

Compressibility
Describes the tendency of the material to deform under pressure, and is therefore related to thickness. Together with roughness and flexibility, this can be used to describe the softness of fabrics (see explanation above).

RESULTS

The results can be analysed in both a qualitative and a quantitative way. For the qualitative analysis, four categories are distinguished [Karana, 2012]:

1. Material properties: which refer to technical and sensorial properties;
2. Product aspects: which refer to the shape, function and production process related to the product;
3. Context of use: how, where and why the interaction related to the product/material takes place;
4. Intangible aspects: are dependent on the user, and are determined by culture and personality.

FAMILIAR MATERIALS

For this study, 13 responses were collected. The respondents were from different nationalities (Dutch, Taiwanese, Colombian and Moroccan) and fell in the age group 21-31. They were predominantly female (11) and all came from a design background.

Material properties
Most of the respondents (9 out of 13) chose wood as a familiar material. The other materials that were chosen were plastic (once as a general term and once PP), denim and grass. Most respondents remarked that materials are familiar to them if they are applied in a lot of products we use or see every day, that are not remarkable or special (such as furniture). Two respondents mentioned that the material wood was familiar to them because it comes from nature. One respondent described that grass was familiar to him, because he knew how it felt and what to expect from it. Another participant described a wooden table that had belonged to her parents and now belonged to her, which was familiar because she could remember it always being there.

It was also mentioned that the feeling of the material is important; a familiar feeling is not surprising, but expected and well-known, and is therefore also comfortable.

Product aspects
The products that were chosen for the embodied materials were primarily furniture (7 times), twice kitchen utensils (bowls and wooden spoons), twice garments (jeans and

slippers), once toys (LEGO) and once a religious wall ornament. All products were fairly common, except for the grass slippers and the religious ornament, without really have any surprising aspects, just everyday products. For two participants it can be concluded that the products they chose were meaningful to them: one that mentioned a table that had belonged to her parents, and one that chose a religious ornament with intricate details that would not be common for most people.

Context of use

The interaction that is associated with familiar materials, is one that is frequent (i.e. happens often) and often out of a 'necessity', such as the use of furniture or kitchen utensils. No special attention is needed to interact with these products; they are always there and often used without really paying attention to them. They are functional, meaning that there is no intrinsic value in the use of the product, but it serves another goal.

Intangible aspects

One of the intangible aspects may have been the label 'natural' to the familiar materials; which is used a as reason why it is familiar. What also was mentioned is that the material is familiar if the origin is known, such as a tree that is turned into wooden products, or grass.

Two participants mentioned that wood was familiar because it was applied in daily products, and that the see wood in the form of trees often.

Quantitative analysis

The sensorial scales filled in by the respondents were analysed statistically to find the properties that significantly contributed to the meaning familiar. The sensorial properties were analysed with a One-Sample t-test, in which the overall mean score for the sensorial items (M=2.85) was taken as the test value. Significance was found for items <0.05. The results of the t-test are shown in Table 10. The properties in bold were found to receive scores significantly above or below the mean score, and are therefore significant. The properties warm, matte, not elastic, opaque and tough were found to be significant. They are shown in Figure 75 in relation to the other properties.

The effect of nationality, gender and age on the attributed

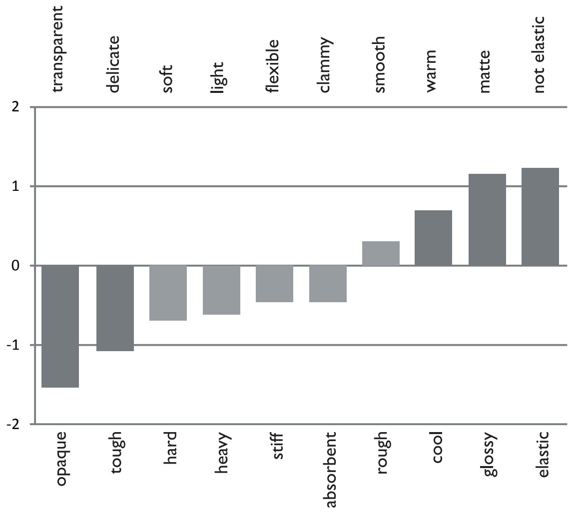


FIGURE 75. SIGNIFICANT PROPERTIES FOR FAMILIAR MATERIALS

Test value = 2.85	*t*	*df*	Sig.(2-tailed)	Mean
Rough-smooth	1.475	12	.166	3.31
Heavy-light	-1.509	12	.157	2.38
Cool-**warm**	2.725	12	.018	3.69
Hard-soft	-1.429	12	.178	2.31
Stiff- flexible	-.898	12	.387	2.54
Glossy-**matte**	4.749	12	.000	4.15
Elastic-**not elastic**	3.641	12	.003	4.23
Opaque - transparent	-5.189	12	.000	1.46
Absorbent- clammy	-.949	12	.361	2.54
Tough-delicate	-4.418	12	.001	1.92

TABLE 10. SIGNIFICANCE OF FAMILIAR MATERIALS

familiar materials

familiar products

properties was tested using a multiple analysis of variance (MANOVA). No significant results were found. The full statistical results are presented at the end of this appendix.

It should be noted that due to the small number of participants (<20), the results obtained by the statistical analysis should not be considered carved in stone.

INTRIGUING MATERIALS

For this study, 13 responses were collected. The respondents were from different nationalities (Dutch, Canadian, Spanish, Turkish and Vietnamese) and fell in the age group 19-29. There were 7 female and 5 male participants, all came from a design background.

Material properties

All 13 respondents chose a different material. The chosen materials can be divided in natural materials (bamboo, wood, reed, leather and mycelium), plastic-like materials (foam, plastics, sustainable plastic, kevlar and micromass), metal-like materials (chain mail metal and ferrofluid) and glass (translucent glass). Respondents mentioned that intriguing materials looked different than they felt, creating a surprising experience. For instance a product made of sustainable plastic looks heavy but is light; translucent glass looks soft but feels hard.

A lot of respondents chose a versatile material; they are intriguing because they can be used in so many ways for different products. Foam can look and feel cheap, but it is essential for the functioning of a lot of products. Wood, bamboo and leather have been used for ages, but by changing the production process, the material experience changes and completely different products can be made by them. The respondent that picked reed mentioned the two-sided character of reed: in nature it does not look interesting, but made into products it has a beautiful natural look, and it lasts very long as material. Than when you paint it, it almost looks like plastic, creating a totally different appearance. The versatility of the material is not obvious however, it remains obscured until the material is explored by means of different shapes and production processes.

Product aspects

The products that the respondents chose can be classified into the categories house ware (bamboo chair, plastic chairs, lamp, wine rack, fruit bowl, clock, glass wall), garments (purse, shoes, bullet proof vest) and packaging (egg carton, wine box). Although the function of most of the products is basic and straightforward, a lot of them have an extra surprising feature. For instance, the clock displays the time by showing the numbers in ferrofluid; the lamp has a top that is made of wood; the wine box is made of fungi instead of cardboard. The products are not archetypes, because the materials are used in a surprising and sometimes unexpected way, that adds an extra dimension to the product.

The production process was mentioned often: by changing the production process the same material can get a completely different appearance and function, which is considered intriguing. For the chain mail material for instance, the respondent mentioned that it gives pleasure when touching it, which is caused by the structure (and production process) rather than the material itself.

More functional properties were also mentioned. For instance, the ability of Kevlar to hold a bullet, the ability of translucent glass to pass light yet not reveal anything, the strong and flexible nature of bamboo. Again, this can be described as unexpected: the fact that a thin material such as Kevlar can hold a bullet; the fact that light can pass through but still nothing can be seen.

Context of use

The interaction with the material is important; some materials that are not well-known have interactions that are not easy to understand. Therefore they invite you to keep playing with them and explore them, such as ferrofluid and micromass. Only by playing with them and seeing how the material reacts it is possible to understand them.

Intangible aspects

Two participants mentioned that the materials they selected were long-lasting. One participant mentioned that the appearance of the selected material changed over time.

The interaction associated with these products is not special in itself, since the products are almost all everyday products. The materials add a surprising touch, which makes the interaction more pleasurable and surprising, and often improves the aesthetics of the product.

Quantitative analysis

The sensorial scales filled in by the respondents were analysed statistically to find the properties that significantly contributed to the meaning intriguing. The sensorial properties were analysed with a One-Sample t-test, in which the overall mean score for the sensorial items ($M=3.18$) was taken as the test value. Significance was found for items <0.05. The results of the t-test are shown in Table 11. The properties in bold were found to receive scores significantly above or below the mean score, and are therefore significant. The properties light, opaque, clammy and tough were found to be significant. They are shown in Figure 76 in relation to the other properties.

The effect of nationality, gender and age on the attributed properties was tested using a multiple analysis of variance (MANOVA). No significant results were

found. The full statistical results are presented at the end of this appendix.
It should be noted that due to the small number of participants (<20), the results obtained by the statistical analysis should not be considered carved in stone.

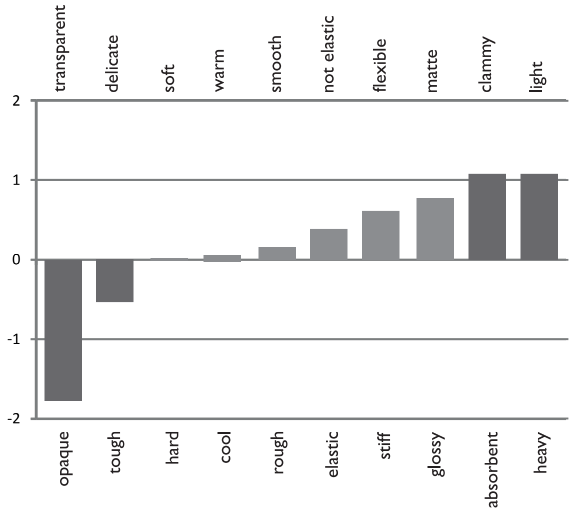


FIGURE 76. SIGNIFICANT PROPERTIES FOR INTRIGUING MATERIALS

EVALUATION

The meanings familiar and intriguing were found to both fit the vision discussed earlier, and aspects of both theses meanings should be embodied in the material. At first glance, it would seem that the meanings are contradictory to each other, since something that is familiar is not intriguing anymore, and something that intrigues us is often not something familiar. However, this does not mean that the properties and experiential aspects associated with these meanings are always opposite to each other. Therefore, in the next paragraph the congruent, contradictory and independent aspects of both meanings are discussed. These will be used as guidelines for the interpretation and use of the meanings for the material design.

Congruent aspects

A lot of natural materials were chosen for both meanings. For familiar materials, naturalness contributed to the meaning itself, whereas for intriguing materials the possibilities of shaping and processing these materials were more relevant.

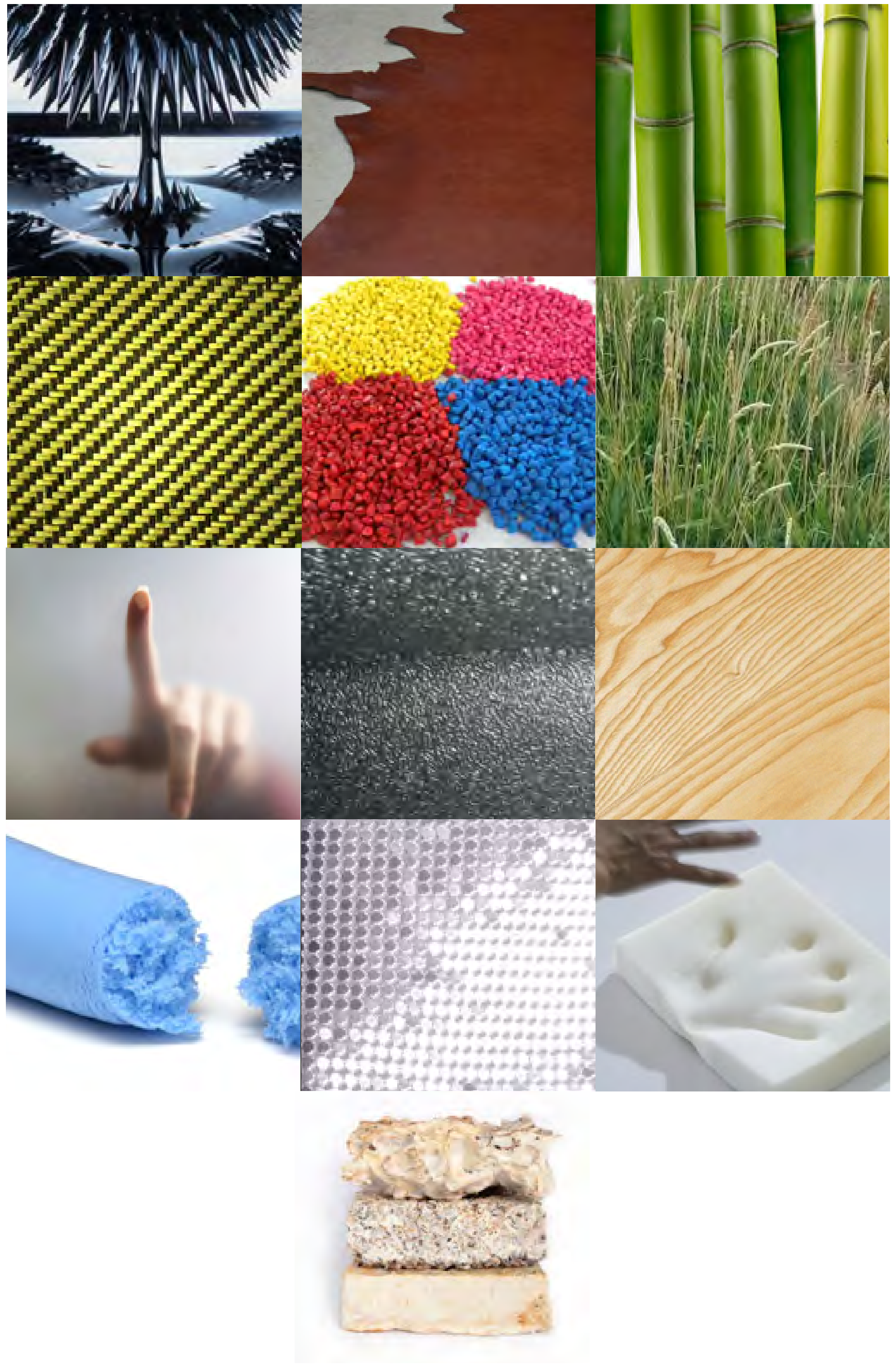
The feeling of the material is important to both meanings. For familiar materials, it is about an expected and well-known feeling, which is related to comfort. For intriguing materials, the feeling is related to exploring the material; playing with it to discover its reactions and understanding it. This relates to an unexpected pleasurable feeling.

The sensorial properties opaque and tough were statistically significant for both meanings. This can be seen most clearly in the familiar materials, since these are predominantly natural.
It was surprising that the products chosen for both meanings were very functional and practical, with archetypical shapes. No special attention is needed to interact with these products; they are always there and often used without really paying attention to them. When intriguing materials are applied to these common products, they get an extra dimension, which is surprising and unexpected. In this case, the product is enhanced by the use of the material, and although the function does not change, the materials are applied in such a way

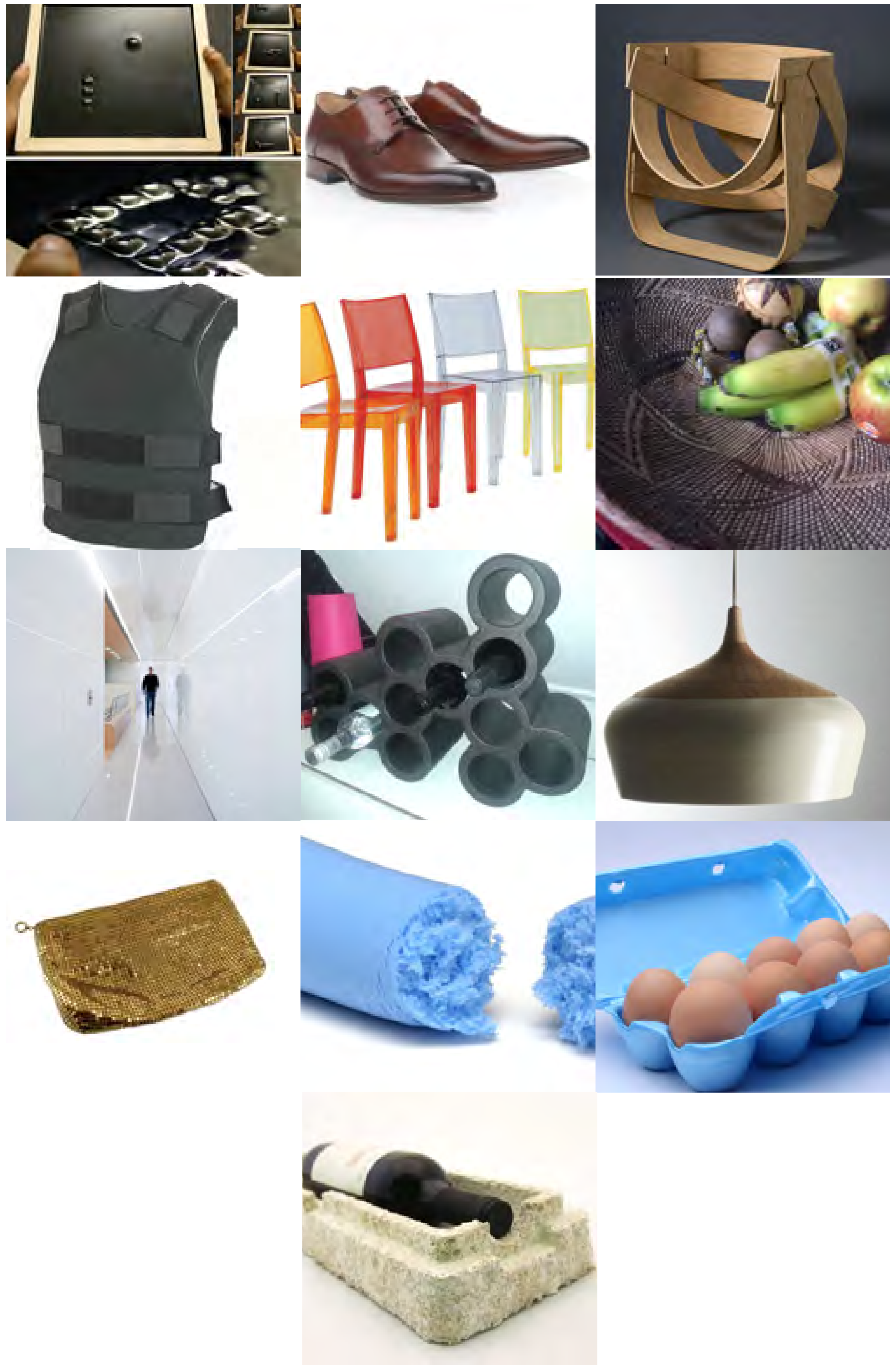
Test value = 3.18	*t*	df	Sig.(2-tailed)	Mean
Rough-smooth	-0.70	12	.945	3.15
Heavy-**light**	2.562	12	.025	4.08
Cool-warm	-.309	12	.762	3.08
Hard-soft	-.408	12	.691	3.00
Stiff- flexible	1.074	12	.304	3.62
Glossy-matte	1.372	12	.195	3.77
Elastic-not elastic	.480	12	.640	3.38
Opaque - transparent	-11.758	12	.000	1.23
Absorbent- **clammy**	3.372	12	.006	4.08
Tough-delicate	-2.483	12	.029	2.46

TABLE 11. SIGNIFICANE FOR INTRIGUING MATERILAS

intriguing materials



intriguing products



that it makes you look at the product again, since it is a little different than expected.

Contradictory aspects

A great contrast is the difference between an expected interaction versus an unexpected interaction. The familiar materials result in an expected interaction; the interaction is well-known, there is no need to discover it. On the other hand, for intriguing materials, the interaction is unknown: the materials first need to be discovered by exploring them and playing with them. This leads to an unexpected interaction.

Because the interaction is unknown, it will remain a surprise. Again, this is contradictory for familiar materials: because the interaction is well-known it will react and feel as expected, making the experience reliable and easily recognizable.

Even though familiar materials could be versatile, they are used in ways that are well-known. The opposite can be said for intriguing materials: even though the materials are often well-known, they are used in diverse, unexpected ways.

Independent aspects

The majority of the significant sensorial properties were independent for both materials: warm, matte and not elastic for familiar materials; light and clammy for intriguing materials.
It was also found that the production process played an important role for intriguing materials, while this was not mentioned for familiar materials.

CONCLUSIONS

As shown above, some aspects of the meanings are congruent, some aspects are contradictory and some aspects are only relevant for one meaning. Since they should both be represented in the material, it is important to understand how they can be used to enhance each other, or to limit each other. In some cases, it might be possible for the material to be both familiar and intriguing at the same time, for other aspects it may be necessary to choose for one of the meanings, or even to create an intriguingly familiar material or a familiar intriguing material.

Interaction

It seems that the interaction between familiar and intriguing materials cannot exist at the same time: it is either an expected interaction, or an unexpected interaction. However, when we think of a material over time, it is clear that the interaction will change; after we have seen and touched an unexpected material innumerable times, we have grown to know it and expect this interaction. On the other hand, if an interaction is expected, it can never grow to become unexpected. Therefore, the decision was made to lean more towards an intriguing interaction, one that is unexpected and surprising at first, but will reduce over time as we explore the material and learn to understand it, becoming more and more familiar and personal to us.

To make the interaction intriguing, from the MDMS research it was found that the material should be playful, unexpected, raise curiosity and be inviting to interact with.

Feeling

The feeling of the material was found to be important for both meanings. The feeling must be comfortable, which was found in familiar materials, and also fits well with the product category, since textiles are often worn close to the skin. A comfortable feeling and a pleasurable feeling lay close together, although the word pleasurable also seems to related to playfulness, to some intrinsic value that can be obtained by touching the material.
It was also decided that the feeling of the material should be warm; this is related to familiar materials, but again it makes sense for the given product category.

It would be preferable to use a natural material, since this was found to fit well with both meanings. However, since it is not yet possible to 3D print natural materials, this may be considered more of a future desire.

Performance

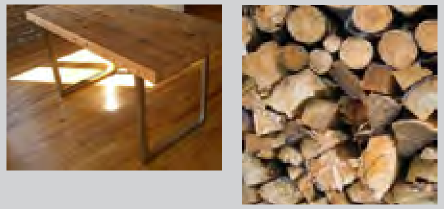
The material should be versatile and reliable. Versatility is a value found in intriguing materials, which is related to the different production processes that can be used to shape the material and influence its properties. Although the production process is in this case already determined, 3D printing allows – more than any other production method – the creation of numerous different structures. These structures can influence the properties of the material, just as the production process can. Therefore, the material should be versatile in a way that different structures can be applied to create different desired properties.

Reliability was found in familiar materials. Although it refers to an interaction that is reliable, since the material is well-known, the interaction will be as expected, it can also be expanded to a more performance-based reliability. In this case, the material is reliable for its function and will not disappoint (by failing to perform its function). It can be said that although the material is reliable, this does not mean that it cannot be surprising. Reliability is in that case more a promise that has to be proven over time.

Product

Products for both meanings were found to be functional and practical, but the use of the material should enhance the product, making it more interesting and inviting to use.
The shapes for products with both familiar as intriguing materials can be described as simple, functional and archetypical. This will be kept for the final product, since garments are designed for a large part to fulfil a functionality. It also fits well with the trend of Slow Fashion, in making a design that is timeless and classic.

WOOD
M/F



It is natural and you find it everywhere around you + in many products.

PP
M/F

It is used for several products. It is cheap and easy to manufacture.

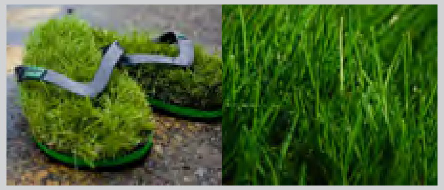
DENIM
M/F

Because I love to wear jeans. The material feels very familiar when I wear jeans.

WOOD
M/F

It's from nature, this can return to nature easily.

GRASS
M/F

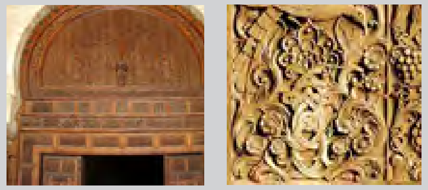


It is one of the first materials that you get in touch with since you are a kid. You know how it feels on your skin, feet, hands. You know the temperature. A piece of grass never disappoints.

WOOD
M/F

A big kitchen table, a fire place.

WOOD
M/F

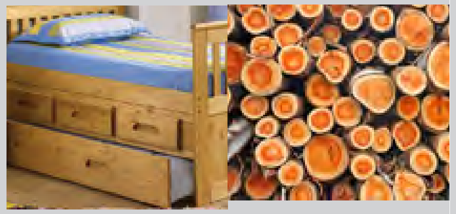


Wood is a familiar material, because it is the origin of lots of daily products such as paper, tables, chairs... It is also from a tree which you see everyday (unless you live in a very
crowded city where no green areas are :p)

PLASTIC
M/F

It is applied commonly in diverse products. Meanwhile it develops various types for different purpose of usage.

WOOD
M/F



I have a lot of products with wood; floor, furniture, accessories etc. It is easy recognisable as wood.

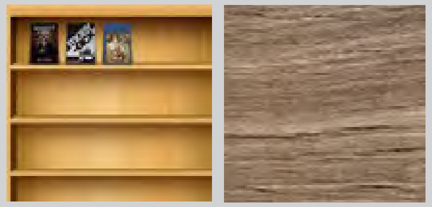
WOOD
M/F

Because it is applied in many many products, and I used to tinker with it myself during study and at home.

WOOD
M/F

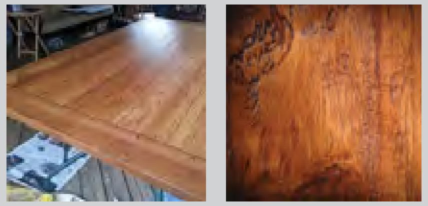
Natural product I use daily. See it when cycling in the natural form of trees and in my house in the products as tables, cooking stuff, small products or as a part of a product. feels
comfortable.

WOOD
M/F



Because I see it a lot in all furniture around me.

WARM WOOD
M/F



This wooden table has been in my parent's place for as long as I can remember. Nowadays it is in my (student) room.

LEATHER
M/F

The ever changing appearance of leather over time and it's ability to adept to be moulded and shaped are fascinating. And the huge lifetime it has when taken proper care for, while other materials just wear until they break.

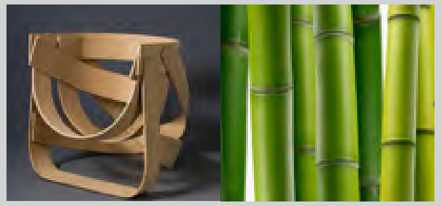
KEVLAR
M/F

It is inspired on the creation of a spiders web, thereby is it really strong. The most intriguing thing about the product, I think, is that it can hold a bullet with a great speed in just a little bit of material.

MYCELIUM
M/F

It is a natural process that produces the material. By controlling or setting boundaries of this process we can influence shape, structure, colour etc.. What is most intriguing is that by understanding the process we can use it to create authentic design and products, although using automatized production.

BAMBOO
M/F



Bamboo is a natural versatile (strong/flexible) material with a nice appeal.

FERROFLUID
M/F

The material can take on different shapes in different circumstances. It is hard to understand how the material works, unless you interact with it for a while. If you play with a magnet and ferrofluid, you can see that it reacts and responds to what you do. So it stays interesting to look at.

MICROMASS
M/F

Because it feels very strange. It is very easy to form, but when it becomes too thin, it sort of falls apart. You just want to keep playing with it.

TRANSLUCENT GLASS
M/F

It feels hard but looks soft. It displays yet not so revealing, raising curiosity. It's clean and bright (allowing light passing through).

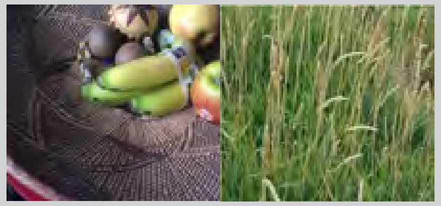
FOAM
M/F

It could result in a lot of different engineering or innovative solutions. Sound insulation, light weight, comfort, shock absorption etc. In a way it could provide a feeling of cheapness, but in other ways its an essential component of many high-tech and high-end products. Also wonderful for prototyping.

WOOD
M/F

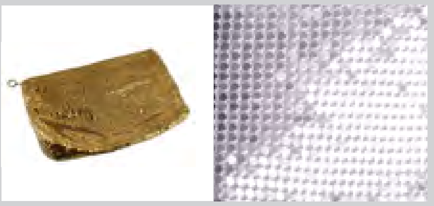
The material has been used for ages by humans. It can be shaped into almost any shape and it is used in many ways. It also comes in many variations and every piece is different.

REED
M/F



It does not look strong or appealing when it is in nature, but you can make cool products that last for ages. It has a beautiful natural look but when you paint it is almost like plastic.

CHAINMAIL
M/F



Metal shaped into mail it gives pleasure when touching.

SUSTAINABLE PLASTIC
M/F

The sustainable plastic has a grainy texture. It is made in a mould and I do like it that even though it is a plastic it isn't perfectly smooth. It looks quite heavy and it is very strong and stiff, so in the product of a wine rack it fits perfectly. When you hold the product it actually is very light. This is a nice and surprising experience.

PLASTIC
M/F

Easy to shape, flexible, colourful and cheap.

H. WORKSHOP FASHION STUDENTS

INTRODUCTION
A workshop 3D printing was given for fashion students of the KABK (Royal Academy of Art), AMFI (Amsterdam Fashion Institute) and HKU (University of Arts Utrecht) as a means to gain creative input. The goal was to see how fashion designers can apply the possibilities of 3D printing and how they envision the roal of 3D printing in fashion in the future.

OBJECTIVE
The goal of the session was to gain creative input for the material concepts. The focus was on creating flexible structures, that could be used as textiles. The main questions were: How to create flexible structures for clothing? How would fashion students use 3D printing in fashion, as substitute for textiles? I want to get them acquainted with 3d printing, and have them think on how to use this in clothing, also for their future career. They should have the opportunity to print some (small) samples that can be used to demonstrate their vision.

PARTICIPANTS
The participants were fashion students from a number of fashion institutes, along with a number of employees. There were 13 participants total, 4 employees and 9 students.

PROCEDURE
The workshop was given at the TU Delft. The participants had signed in voluntarily, the workshop was not part of a course. Three 3D printers were arranged for the workshop, courtesy of MTB3D. The participants were asked in advance to install the software of Cura and to bring a laptop.

The planning of the workshop was the following:

13:30- 13:45	walk in
13:45- 14:00	presentation and explanation of the goal
14:00- 14:45	preparation of a model and 3D printing
14:45- 15:00	coffee break
15:00- 15:45	brainstorm: 3D printing textiles
15:45- 16:30	brainstorm: 3D printing in fashion
16:30- 17:00	short presentations

First, a short presentation was given to explain the goal of the workshop, the working principle of 3D printing and how 3D printing can be used to create textiles. After that, the students were given an .STL model on their laptop, that they were asked to open in Cura to get familiar with the interface. Even though the 3D printers that were present were not Ultimakers, it was thought best to use Cura as a software because of its user-friendly interface. Since Cura was not compatible with the printers that were there, the models were put on SD-cards in the printers in advance. Then the model that the students had viewed was printed 4 times on each printer, so every participant could take one home.

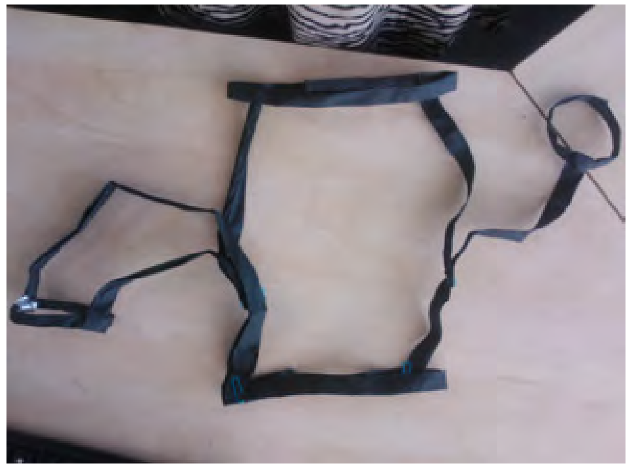
The next activity was a brainstorm session, in which the students were asked to work in groups and think of how to design a 3D printed textile. In the next phase, the students were asked to brainstorm about how to apply this in a 3D printed piece of clothing and to make a small model.

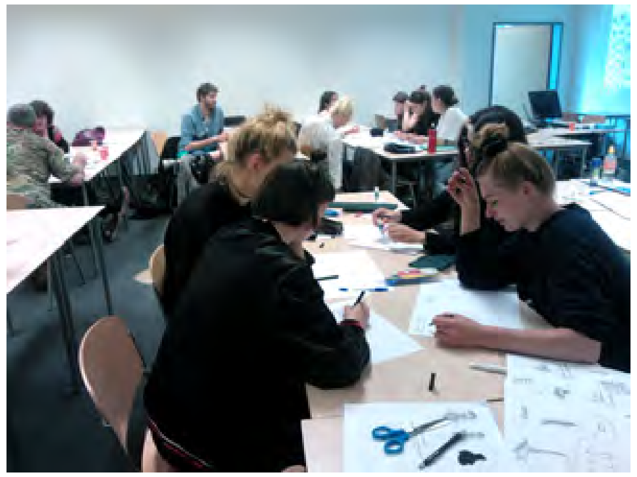
RESULTS
On these and the following pages, some pictures of the workshop and the results are shown. The fashion students had some trouble brainstorming, since this is not something they were familiar with from their own education. They also mentioned they were not used to work in groups at all. However, they had some interesting ideas regarding 3D printing and what it could mean for fashion.

- Patterns: the students wanted to include patterns into the 3D printed clothing, for instance by printing different colours at once (more than 2).
- Functional aspects: the more functional aspects of 3D printed clothing that were identified were: no need for finishings such as hems; including closures and pockets in the 3D printed clothing; labels/ washing instructions included; no standard sizing anymore; patterns that are continuous across the garment.
- Added benefits: priting flavours into clothing, for instance with latex; print cellular structures (such as distels); print a "hugging sweater"; print with kinetc materials that harden on impact (to secretly add i.e. knee protection to clothing, because children don't want to wear it).
- Materials: genetically modified animals (sheep that produce wool high in wax; controllable caterpillars; cows that grow in a certain shape to 3D print leather); clothing that sticks to your body (such as distels).
- Technology: dual printing technology in which one printing head extrudes plastic and the other yarn. The yarn is formed into shapes and fixed in certain places with the plastic, to create both 3D-structures and soft materials at once.
- Structures: interested in the possibilities of 3D printing to create organic structures or origami structures.
- "Technostalgia": printing knitted structures

Some indirect results, that were obtained from observing the participants and talking to them, were the facts that the fashion students were mostly interested in the opportunities of 3D printing to create 3-dimensional parts that they otherwise could not create. This was interesting for them, since they are trained to translate a "feeling" or "image" to a collection of clothing, rather than thinking about the opportunities that 3D printing offers, they were interested in ways they could translate their vision to clothing. This is an interesting observation, since it would seem that the driving force for 3D printed clothing will not (necessarily) come from fashion designers.
Also, their knowledge of 3D modelling was very limited, which means they would need to cooperate with another party that could produce the models for them. Some of the students were used to designing from a material point of view, they would get a material such as plastic bags assigned and would have to create a piece of clothing out of it.

The resulting designs that were sketched or created by the students were not highly innovative and showed influences of the designs they had been shown. However, this could be a consequence of the fact that they are not textile designers themselves, they design the clothing or the vision and chose the fabrics from what already exists and is possible.





I. WORKSHOP MATERIAL DRIVEN DESIGN

INTRODUCTION

A workshop Material Driven Design was executed in order to help with translating meanings to materials and products. A number of students was asked to explore one of the 3D printed textiles.

OBJECTIVE

The goal of the workshop was finding out how other students evaluate materials based on a given meaning and how this can be translated into meaningful product design. For the students, it was a way to experience how a meaning can contribute to the design of a meaning.

PARTICIPANTS

The participants were students of Industrial Design Engineering, in the master phase, that were participating in the course Materials for Design given by dr. E. Karana. A total of 12 students participated in the workshop.

PROCEDURE

The workshop was given at the TU Delft. It was given as part of a course, although it was not mandatory to participate. The students had some prior knowledge on designing materials.

The schedule of the workshop was the following:

14:45- 14:55	introduction
15:00- 15:15	material exploration
15:15- 15:25	brainstorm: designing the material
15:25- 15:35	brainstorm: designing a product
15:35- 15:45	short presentations

Due to deadlines for other courses, of the 30 expected students only 12 were present, therefore the workshop was cut shorter than initially planned.

In the introduction, the students were explained the steps of the material driven design process, what the vision was and how the meanings were evoked.

The students were asked to work in groups of 2 or 3 people. They were given one of 4 different 3D printed textiles to work with (two groups received the same material), as well as a material datasheet explaining the material, and the MoM models for the meanings intriguing and familiar.

In the material exploration phase they were asked to examine the material and write down in what ways they thought it fit both meanings, or in which ways it did not.

For the next brainstorm, the students were asked to improve the material for both meanings, based on their results from before. They were asked to maintain the solution principle of the sample, but they could change the shape, size, material, etc. in order to make it fit the meanings in a better way.

After this, the students were asked to use the sample they had received or designed themselves to design a product.

RESULTS

The results are shown below per solution principle.

Thin springs

The results of the material exploration are shown in the table below.

Intriguing	**Familiar**
Evokes interaction; you want to bend it, to see what happens: it raises curiosity	Geometrical pattern
Soft but yet hard	Reliable; looks like metal but seems to break easily (looks more reliable than it is, the fine structure is more sturdy)
Surprising; because it is flexible, light and seems rigid	Easy to work with because it is flexible
Fragile; seems stronger (because of structure) than it is. Relates to a spring but put too much force and it breaks.	Elasticity like rubber
Pattern changes when deformed	Vibrates
	Resembles a doormat

It was concluded that this material was more intriguing than familiar. Some solutions to make the material feel more familiar were:

- Changing the shape to resemble woven/knitted textiles (although the shape is part of the attraction);
- Making it thicker, although this would mean a loss of flexibility;
- Creating a denser pattern to make it more covering (for instance squares), to make it less brittle and more difference in exposure;
- Changing the material to a more flexible material (such as silicone).

Two groups designed a new product with this material. The first group designed a yoga mat (as shown in Figure 79), in which the size of the elements differs along the mat. When rolling it up the small structure allows it to be rolled up at a small angle on one end, and a big angle at the other end. This makes optimal use of the possibility to vary the structure in one product.

The other group designed a brace, as shown in Figure 77. The brace allows protection of one movement that should be limited, and supports the other movements. It would be an added value because of the openness of

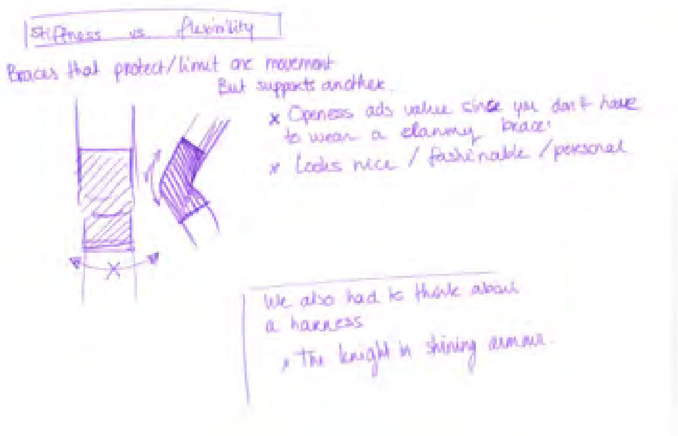


FIGURE 77. BRACE DESIGN

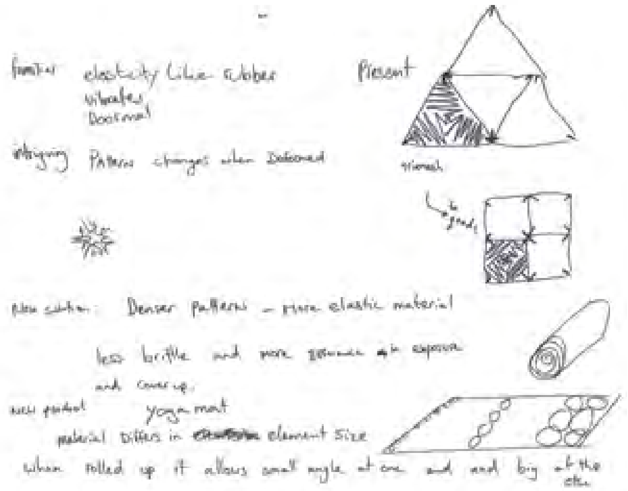


FIGURE 79. YIOGA MAT

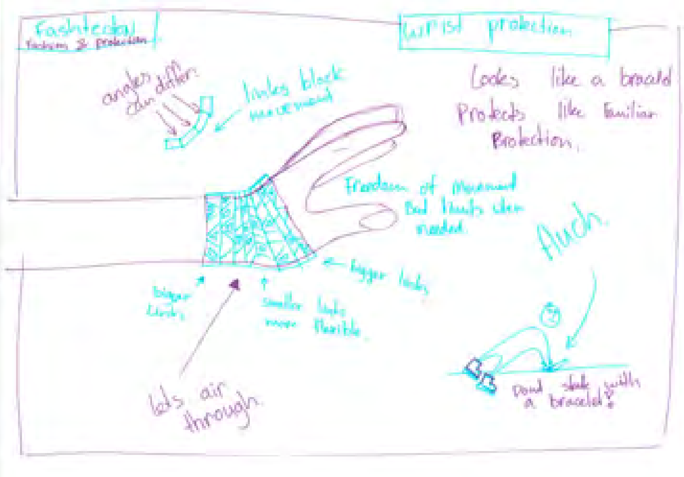


FIGURE 78. WRIST PROTECTION

the material, which is the opposite of the clammy braces that exist today. Also, the structure looks nicer and more personal.

Chainmail links

The results of the material exploration are shown in the table below.

Intriguing	**Familiar**
Bending direction	Material
Aesthetic pattern	Colour
Elastic feeling	Resembles *Ministeck*
Aggregation	
Material sound	
The lightness of the links	

Although the material was already rated as more intriguing than familiar, the group decided to try and make it even more intriguing rather than familiar. One suggestion to make the material more familiar was by making it heavier, for instance by making it out of steel.

Ideas to make the material more intriguing were:

- Change the colour to black to make it look more like a textile;
- Create different sized links in one product;
- Change the shape in order to control the flexibility of the material and the bending direction.

The product they designed was a promotional samba skirt for the World Championship Football. This concept was based on the rattling sound the material makes when moved.

Hinges

The results of the material exploration are shown in the table below.

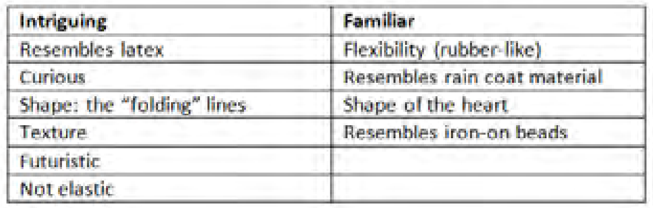
Intriguing	**Familiar**
Every shape is different	Hinge connection
Flexibility	Triangular shape
Weight	Metal-like colour
The continuous surface (although they are all separate parts)	

This group also chose to make the material more intriguing. They suggested using a flexible material for the links instead of a rigid one. Another suggestion was to change the flat shape of the links to a 3D-shape, for instance with a rounded top.

The concept they created was called Fashtection – Fashion & Protection. The product was a wrist protection brace, that looks like a bracelet but protects like familiar protection, shown in Figure 78. The links block the movement at different angles, while also providing freedom of movement and letting air through. This is caused by differing the shape and size of the links.

Flexible material

The results of the material exploration are shown in the table below.



Intriguing	**Familiar**
Resembles latex	Flexibility (rubber-like)
Curious	Resembles rain coat material
Shape: the "folding" lines	Shape of the heart
Texture	Resembles iron-on beads
Futuristic	
Not elastic	

The group thought the material was more intriguing than familiar, and suggested the following to make it more familiar:

- Change the structure to resemble traditional textiles (i.e. woven);
- Make the pattern finer;
- Use organic, flowing lines;
- Mimic the structure of lace.

They designed a number of product ideas, such as outdoor furniture/pillows, poncho's and rain protection and curtains.

DISCUSSION

Both the sensorial/experiential properties of the MSP's were used, as well as the more functional properties, such as flexibility versus stiffness. The students with the chainmail MSP and thin structures used the possibilities of the MSP's to apply local structure changes to adjust the properties. Most of the products they designed were not clothing, but other wearables. Two groups designed a brace. The braces utilized the possibilities of the MSP's to be rigid or flexible, so that they could be used to control and limit the movements as a means of protection. Another group designed a yoga mat, which utilized changes in structure to facilitate rolling it up.

From the product designs, it became clear that the chainmail and thin structure MSP's were not really considered textiles, but more as improvement of rigid plastic parts, due to their breathability and flexibility. For the flexible material, the opportunities of AM were not utilized, the product directions they came up with used the MSP to replace other rubber-like materials. It might be ossible to conclude from this that the flexible material on its own is not intriguing, but that it would an intriguing structure to enhance it.

The meanings were not used for both material and product design, but only for the evaluation of the MSP's. Most samples were considered more intriguing than familiar. For this meaning, the function of the products was enhanced by the use of the MSP, although the MSP itself did not dictate the function. Suggestions to make the samples more familiar were to mimic the structure of traditional textiles, or to change the material it is made of to something that is more familiar.

J. CELLULOSE

This section gives an overview of the properties of cellulose, and its potential for 3D printing. This material was researched for several reasons. First of all, cellulose is one of the most common materials used for often used textiles (discussed in section 5.4). Second, the properties of cellulose have been regarded as very desirable for textiles. Third, it has been opted that being able to print cellulose would accelerate and increase the possibilities of printing textiles and clothing [J. Mikkonen 2014, pers. comm., 7 April].

WHY IS CELLULOSE DESIRABLE FOR TEXTILES?

Cellulose is an abundant, renewable material. It can be regenerated from material that would otherwise be waste material, such as cotton linters that are too short to be spun, or recycled wood. However, it should be noted that not the material itself has properties that are desirable for textiles, but rather that the shape and structure of the fiber are responsible for these properties. This becomes clear when taking a look at cotton fibers. Cotton fibers grow as a thin-walled hollow tube of cellulose inside the cotton boll. It develops an internal structure as a result of the deposition of thin cellulose layers onto each other [Goswami, 2004]. These "growth rings" are alternating solid and porous. Once the cotton boll opens, the fibers lose their moisture and obtain a kidney-shaped cross section [Goswami, 2004]. In longitudinal direction, the fibers are not straight but slightly twisted.

All the factors described above contribute to the desirability of cotton for clothing. The longitudinal twist and surface texture allow the fibers to be twisted and adhere to each other. The alternating layers of fibers in the cellulose and its cross section allow cotton to have good warmth-retention and absorbent properties.

APPLICATIONS OF CELLULOSE

Cellulose is one of the main building blocks of all natural materials. It exists in the form of fibers in wood, cotton and other plants and is the most common organic polymer [Klemm et al., 2005]. Cotton consists of more than 90% cellulose, while the cellulose content of wood is around 40-50%. Cellulose has a unique structure, that allows it to be used for a large number of different applications [Klemm et al., 2005].

Cellulose is often used as a raw material, most commonly in the production of paper and cardboard. In this case wood pulp is the raw material source for processing. Cellulose fibers are also regenerated to be used for the production of yarns for the production of viscose, acetate rayon, cupro and Lyocell. In both these cases, the cellulose fiber is kept intact.

When chemically extracting the cellulose polymer, it is possible to create a thermoplastic material called celluloid [Klemm et al., 2005] that was used to produce films in the fifties before the discovery of acetate (Figure 80). Another well-known material made from cellulose is cellophane, commonly used as food packaging material (Figure 81).

The examples above show that cellulose in essence is nothing more than a polymer, of which the properties depend on the manner in which it was produced. This means it would theoretically be possible to create a filament suitable for material extrusion, however, the results of printing with this material would be similar to printing with other thermoplastics. Therefore, it can be concluded that to recreate the properties of cellulose-based fabrics, it is important to keep the fiber intact and to recreate the hierarchical structure of textiles.


FIGURE 80. CELLULOSE ACETATE


FIGURE 81. CELLOPHANE


FIGURE 82. 'WELDED' PP YARN

Cellulose pulp
Ingredients: recycled paper, water, a number of binders.

1. The recycled paper is shredded and boiling water is poured over it, until it is completely submerged.
2. This mixture is left to cool to room temperature.
3. Once the mixture is cooled, the excess water is poured out, and the mixture is transferred to a blender.
4. The mixture is shredded by the blender, if necessary with the addition of extra water, until it becomes a smooth paste.
5. After this, the remaining water in the mixture can either be squeezed out by hand, to obtain a relatively wet pulp, or placed into a coarsely woven cloth ad squeezed to obtain a relatively dry pulp.
6. As a final step, the pulp can then be mixed by the desired binder.

FIGURE 83. PREPARATION OF CELLOSE PULP

REGENERATED CELLULOSE

This section briefly describes the process of regenerating cellulose fibers in the production of yarns for textile production.

Cotton linters or wood pulp are generally used as a source for regenerating cellulose fibers [Goswami, 2004]. The first step in the fiber production is removing the lignin, which keeps the fibers together. This involves treating the wood pulp with caustic soda or an organic solvent. The viscous solution that results is spun in a spinning process. There are different spinning processes, one that is commonly used for the production of viscose is dry-jet wet spinning, while dry spinning is more common for the production of acetate. In all spinning methods, a spinneret is used to extrude the material through.

The resulting filaments are either kept intact and used as filament fiber, or cut into smaller fibers and treated in order to change their properties.

It is interesting to see that the process for producing fibers or filament from cellulose has a lot of similarities with the material extrusion process. Since earlier in this report it was shown that creating smaller structures resulted in more textile-like materials, an interesting topic for future research would be to try and mimic the process parameters of regenerating cellulose in a 3D printing process. As a suggested result, a small test was performed with a mono-filament made of PP, which was "welded" in certain areas to create a structure. The resulting material is shown in Figure 82. This shows a possible way to 3D print using multiple, thinner filaments.

CELLULOSE 3D PRINTING EXPERIMENTS

In order to be able to print cellulose fibers as a whole, a suitable printing process needed to be found. Material extrusion was found to be the most suitable process, and also the most readily available process for experimenting. Since cellulose fibers have poor heat properties, it was decided to experiment with cold paste extrusion, similar as used for clays, rather than filament extrusion in which the plastic has to be heated for extrusion.
A number of experiments was conducted in order to find out A) what the potential is of extruding cellulose fibers and B) whether the resulting material would fit the envisioned material experience.

Set-up

A cellulose paste (more commonly known as cellulose pulp) was prepared. Recycled paper was used as a readily available source with a high cellulose content. The pulp was prepared as described in Figure 83.

From the experiments, it became evident that it was necessary to mix the cellulose fibers with a binder, in order to extrude them through a syringe or nozzle. The function of the binder is to allow the cellulose fibers to slide past each other rather than adhere to each other.

The binders that were used for the experiments were PVA, natural latex and flexible acrylic. The resulting mixture was placed in a syringe with a nozzle size of 5 mm in diameter, or 1,5 mm in diameter and attempted to be extruded. The results of the experiments are shown in Table 12. If the mixture could not be extruded through the largest nozzle size (ø5 mm), it was pressed flat instead in order to judge its material properties when dry.

It was found that the flexible acrylic was the best binder, since the resulting material was also flexible. At least 30-40% binder (by weight) was necessary to be able to extrude the mixture (Figure 84). The smaller the cellulose fibers, the easier it is to extrude the mixture. When applying pressure, the excess water content is pressed out of the mixture first.

No.	Ingredients	Process-ability	Resulting material
1a.	70g wet pulp + 20g PVA	Does not extrude (ø5 mm)	Hard, very rigid material. Strong. Bottom surface is very smooth.
1b.	70g wet pulp + 33g PVA	Extrudes well (ø 1,5 mm)	Hard, very rigid material. Strong. Bottom surface is very smooth.
2	23g dry pulp + 15g latex	The use of latex results in a non-slipping mixture, which cannot be extruded.	Hard material, surface texture is rubbery. Over time the material dried out and became brittle.
3	23g wet pulp + 8g acrylic	Extrudes well (ø5 mm), not so well for smaller nozzle (ø 1,5 mm)	Flexible material. Relatively strong. Has a very nice surface texture on the bottom surface, smooth and velvet-like.
4	18g dry pulp + 11g acrylic	Extrudes poorly (ø5 mm)	Flexible material. Relatively strong. Has a very nice surface texture on the bottom surface, smooth and velvet-like.
5	20g dry pulp + 20g acrylic	Extrudes well (ø 1,5 mm)	Flexible material. Relatively strong. Has a very nice surface texture on the bottom surface, smooth and velvet-like.
7	33g wet pulp (TP) +17g acrylic	Does not extrude	Flexible material, tears more easily. The fibers seem to be more clustered together, creating a 'cloudy' structure. Bottom and top surface feel pleasant and soft.

TABLE 12. CELLULOSE EXPERIMENTS

3D PRINTING

In addition, some experiments were performed in order to test whether the mixture could be 3D printed. For this, an Ultimaker Original printer was converted to print with a syringe. This set-up is shown in Figure 85. The syringe is held by a holder, attached to the print head. The filament is positioned on top of the syringe, and thus pushes the paste out of the syringe when the printer pulls it through.

Although it is possible to push the cellulose mixture out of the syringe by hand, the printer is unable to press it out.

Only water is forced out of the mixture, the fibers itself cannot be extruded. A different nozzle shape was tried in addition, which is shown in Figure 86, although unfortunately this also did not work: only water is pressured out of the mixture. This led to the assumption that the fibers need a better binder in order to be extruded; one that allows them to slide past each other more easily.

CONCLUSIONS

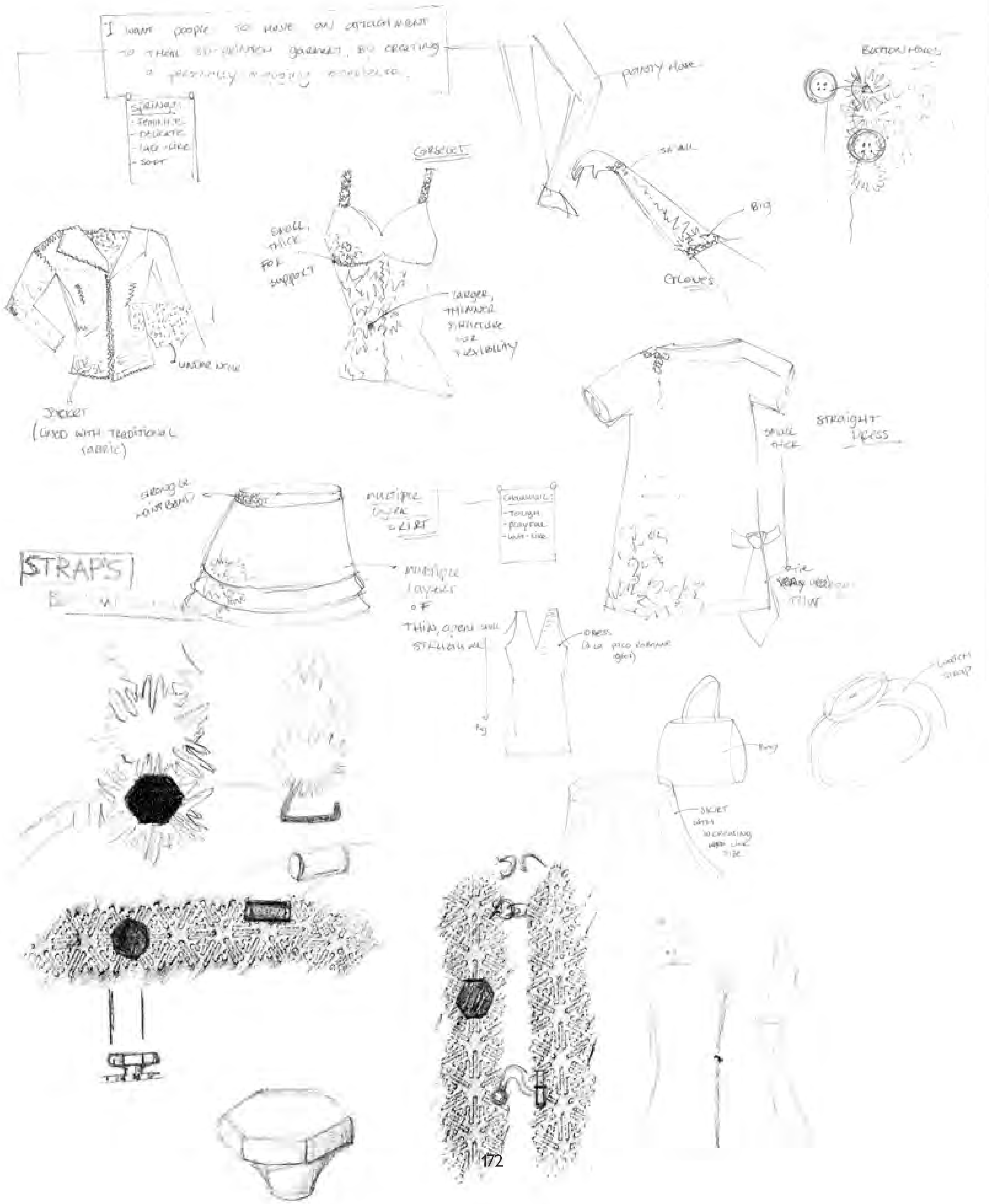
From the literature review and the experiments, it has become clear that the most promising area for 3D printing cellulose is a process in which the fibers are kept intact. The tests have shown that there is definitely potential for a Material Extrusion process using a cellulose pulp mixed with a binder. Of course, these initial tests are not sufficient and should definitely be expanded on, but they do function as a proof of concept. Some recommendations that can be given for future testing include decreasing the size of the fibers even further (for this more professional equipment will be needed), experimenting with different (bio-based) binders, and researching ways in which the drying time can be reduced. It is recommended that this is done in collaboration with a material scientist/engineer.

FIGURE 84. EXTRUDING THE CELLULOSE MIXTURE

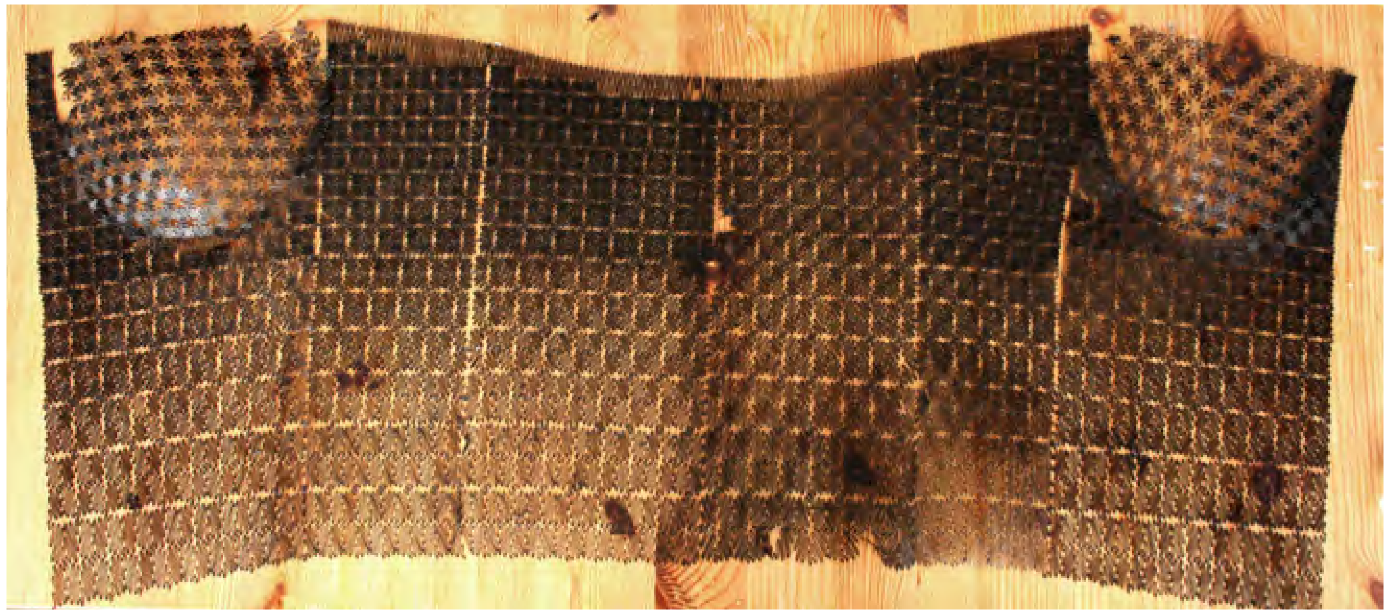
FIGURE 85. CELLULOSE PRINTING SET UP

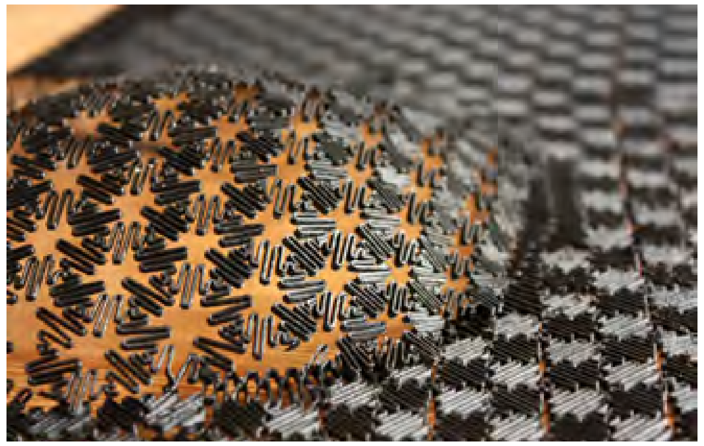
FIGURE 86. ALTERNATIVE NOZZLE

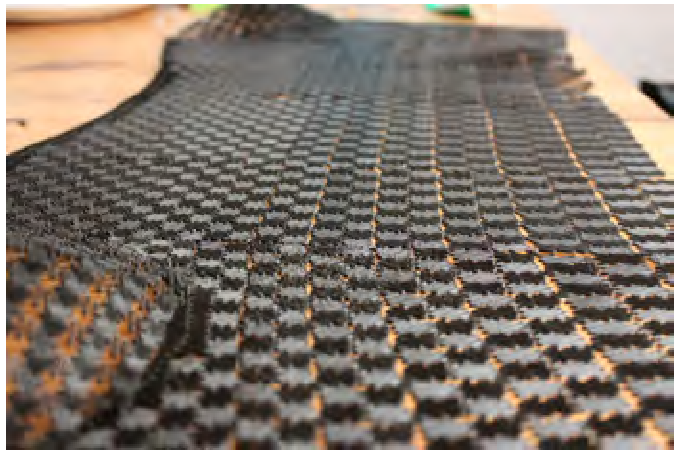
K. DESIGN PROCESS- IDEATION



L. PROTOTYPING







© Philippe Halsman / Magnum Photos

© Philippe Halsman / Magnum Photos

IMAGES BY PHILIPPE HALSMAN