Designing with 3D Printed Textiles

A case study of Material Driven Design

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***Abstract*— This paper describes the findings and results of a design project with the goal to design a wearable garment using 3D Printed textiles, which not only has functional or environmental superiorities, but also experiential ones. 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 chosen material is the point of departure. As this method has not yet been applied on a project involving additive manufacturing, another goal is to explore how the MDD method can be used in a project where AM is the primary production method. For MDD, this means that the material that is usually the starting point, should now be a combination of material, structure and process (MSP), and that it is important to understand how these aspects influence each other. The final MSP concept can be locally varied to create property gradients, which results in a range of slightly different MSP's. These materials have been embodied in the design of a corselet, which utilizes the different properties of the MSP. A number of recommendations has been given for the development of future 3D Printed MSP's.**

Additive manufacturing, textiles, 3D Printed textiles, Material Driven Design, garments

1. Introduction

Until recently, applications of 3D Printing or Additive Manufacturing (AM) in the field of fashion have been limited to accessories and shoes, instead of garments. This could be explained by the limited set of materials available for AM that showed potential for comfortable garments.

Pioneering work on AM fabrication of fabric-like materials was presented by Evenhuis and Kyttanen (2003), whose method included projecting a textile pattern onto a particular surface, for instance a piece of clothing, and generating a 3-dimensional computer model of the pattern [1]. The result of this process is a complex model of interwoven links, which resembles chainmail structures as used for armour in the Middle Ages.

Since then, the potential for creating textiles by means of AM has mostly been attributed to these structures. They are often called multiple assemblies, since in essence they consist of separate parts [2]. The only limiting factors attributed to these structures are the limitations of existing CAD modelling tools, for instance the ability to "drape" the AM textile across a curved surface (such as the human body), which was extensively researched by Bingham et al [3], Crookston et al. [4] and Johnson et al. [5]. Proposed applications for these textiles were mainly functional, such as stab-resistant wearables [5] and high-performance or smart textiles [3].

However, the development of flexible materials suitable for AM seems to have renewed interest in other possibilities for the production of 3D Printed textiles. Mikkonen et al. [6] have tested the tensile strength of one of these flexible materials to determine whether it would be a suitable replacement for fabrics.

At the same time, the possibilities of AM have not gone unnoticed in the world of fashion. The form freedom that AM provides has been utilised to create accessories that could not have been created without this technology. Only a few designers have tried their hand at making entire garments using AM. For example, Iris van Herpen, in collaboration with architects such as Beesley and Koerner and designer Neri Oxman, has designed and fabricated numerous sculptural AM garments [7]. These garments were 3D Printed using rigid and flexible materials developed especially for this purpose. The emphasis of such work usually lies on finding a way to translate the vision of the designer and to make a statement, as is common for art, and not in creating objetcs for daily use. As a result, most of the 3D Printed garments illustrate ground-breaking developments but do not represent comfortable, ready-to-wear clothing. Considering the developments of AM, the potential of using 3D Printed textiles in ready-to-wear garments becomes apparent: they can be more comfortable, personalized and suitable for daily use. In this paper, the findings and results of a design project that adresses this gap are presented.

The ambition of this project was to develop a wearable garment that not only has functional or environmental superiorities (e.g. comfort, personalised, no material waste), but also experiential ones, i.e. how a material/product is perceived by people (e.g. unique tactile experiences, the feeling brought on by unique garments).

The approach is grounded on a recently developed method by Karana et al. (in review) 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.

2. Method

For this design project, a Material Driven Design (MDD) method was implemented [8]. The goal of the MDD method is to facilitate product design when a material is the main driver. The method is based on developing a thorough understanding of the material 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. 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 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, and friendly) that can be translated to material properties using Meaning Driven Material Selection (MDMS) [9]. Finally, in the fourth step, the findings obtained in the previous steps are used to create material/product concepts.

It is important to emphasize that the MDD method has been developed for material driven projects in which a particular material or material family (e.g. oak, cork, a smart composite, bio-plastics, etc.) is used as the point of departure for the design process. In this project, the intention is to explore how this method can be applied in a design project where not only the (type of) material is set, but where AM is defined as the primary production method.

According to MDD 3D Printed textiles are classified as a semi-developed material [8]; a novel material of which the boundaries have not yet been determined. This material can be described as a combination of material, structure, and process (MSP), since these three factors influence each other and the properties of the 3D Printed textile. Therefore, all three are important to the outcome of the final material. The results of the MDD method can be used to determine the boundaries of this MSP, to find a meaningful application and to give feedback for further development.

3. Application of MDD Method in Designing With 3D Printed Textiles

In this section, the application of the MDD method to a design project 'Designing With 3D Printed Textiles' is described.

3.1. Understanding the material

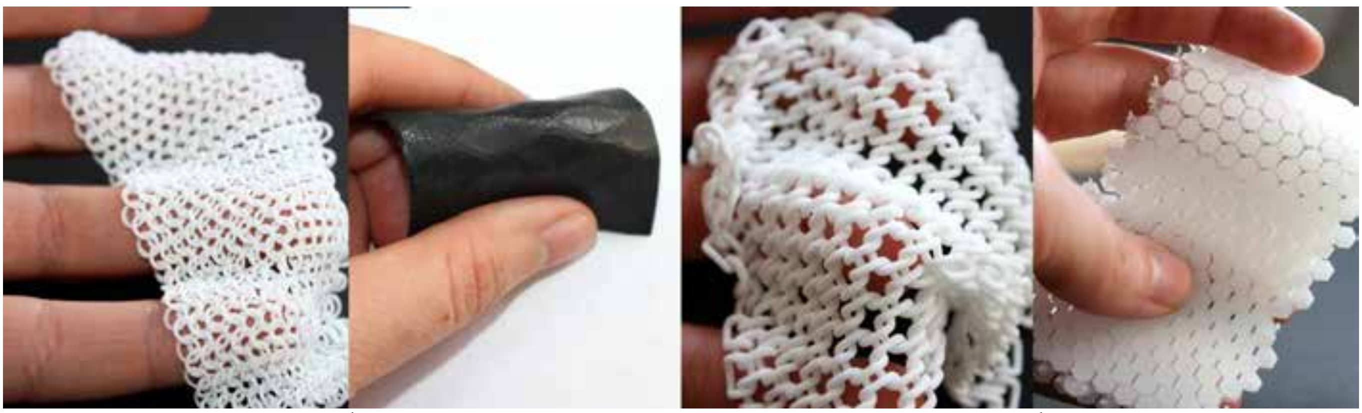
In accordance with the MDD method, the first step of the process is understanding the material and characterizing it technically and experientially. It is encouraged to 'tinker' with the material, to get insights as to how it behaves.

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. Several samples are shown in Fig. 1. This was an iterative process, in which different possible designs were created and their feasibility as a 3D Printed textile was evaluated. It was found that different combinations of MSP result in different materials that can have different, meaningingful applications in different contexts.

Three topics were important to understand the context of 3D Printed textiles: the process (i.e. 3D Printing), the product (i.e. textiles), and the MSP itself (i.e. 3D Printed textiles). Since the boundaries of the material had not yet previously been defined, it was necessary to analyse all three domains in order to find its limits and opportunities. This was done by means of literature studies, benchmarking and explorative sessions using the collected and fabricated samples. The most important results of this analysis are summarized below.

a) 3D Printing

Additive 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 [3]. These slices correspond directly to the layers that are built by the AM process, allowing the production of virtually any geometry. Materials that can currently be processed by AM include polymers, metals and ceramics.



a. b. c. d.

Figure 1. Samples of 3D Printed textiles

The recent developments of AM have set high expectations for the future of this technology. As a result, the tone with which is spoken about 3D Printing in the media is one of excitement, anticipation and innovation, as is consistent with the Gartner Hype Cycle, where 3D Printing is now on its way to the top. Although the positive image of the AM 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 could clash with the expectations of the user, which may result in a negative attitude towards the product.

b) Textiles

Flexibility is the most important property for textiles, since without flexibility no wearable garment can be produced. However, there are more properties that are important for textiles, including warmth retention and absorption, softness and elasticity [10], [11], and that make them suitable to wear close to the skin. In order to understand why textiles have these properties, the structure and properties were analysed on four different levels: garment, textile, yarn and fiber. It is possible to distinguish a main structure for each level, 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, for instance warmth retention is caused by porosity in the structure [10].

However, although the hierarchical structure is important in order to create the desired properties, this brings challenges to the production of this structure. For each structural level, a different production process is necessary, of which the limitations and waste are accumulated across the chain.

c) 3D Printed textiles

Classification

The main requirement for textiles created by means of 3D Printing was found to be flexibility, in order for them to be applied in wearable garments. Therefore, a classification is proposed based on the main source of the flexibility, as depicted in Fig. 2. 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 discrete bodies that make up multiple assemblies. Material-based refers to the fact that the flexibility is obtained mainly due to the characteristics of the material, by the use of flexible materials such as elastomers. Finally, an overlapping category can be identified in which flexibility is obtained by a designed single body structure that incorporates variable thicknesses, which is named thin structures.

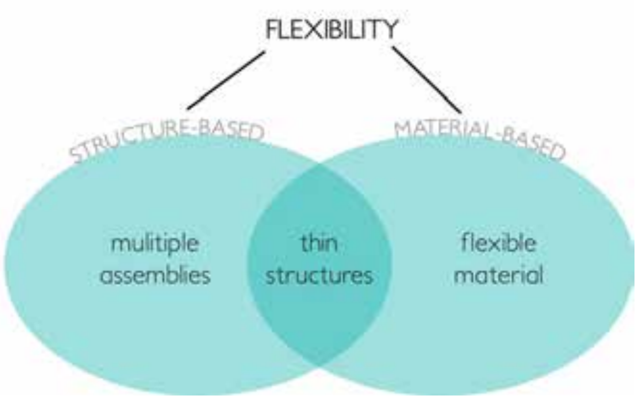


Figure 2. Classification of 3D Printed Textiles

Experiential characterisation

To explore the experiential properties of the material, the collected samples were analysed by means of an explorative user study. In individual sessions >10 participants were shown the collected 3D Printed textile samples. While the participants were invited to touch and interact with the samples, their reactions, remarks, and interactions with the material were evaluated. It was found that 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.

Although all samples were flexible, only one of the samples was explicitly described as a textile by the participants (Fig. 1a). The participants expressed that the fine structure of multiple assemblies made it feel softer and more drapable. The other samples were not seen as textiles. These results indicate that in order for the material to resemble a textile and obtain properties desired for textiles, such as softness and drapability, the macro-structure should be as fine as possible.

In addition to the user studies, following the MDD method, a material benchmark was conducted in order to find examples of AM applied in the area of garments. Most application areas were found in the categories of jewellery and accessories (bags, shoes and hats). In the category of clothing, most application areas were dresses, underwear (corsets), swimwear (bikini) and more sculptural “armours”.

3.2. Creating a materials experience vision

After the first step, according to the MDD method it is expected that the designer knows and understands the material. In order to find new, unique applications for the material, it is suggested to create a materials experience vision, which expresses the role of the material in the envisioned user experience, as well as the relation it has to the context [8].

In this design project, the vision is related to the findings from the analysis of the three domains mentioned earlier: 3D Printing, textiles, and 3D Printed textiles.

The use of a new and innovative production process should be utilized to the fullest in order to be of most value. Personalization is one of the key aspects; garments can be produced to the exact measurements of people’s bodies, while still being economically viable. Also, the opportunities for including property gradients in the product to be printed (material or structural) are a unique benefit of the process.

Looking at the current life cycle of garments, it becomes clear that it is driven by fluctuations in fashion, which often leads to the early disposal of garments. As a reaction to this, the trend of slow fashion is emerging. Slow fashion is centred on design for long term use and wear, with concern for the entire life cycle of the product [12]. It strives to achieve minimum impact and waste, by increasing the aesthetic, functional and emotional value of the garment [13]. This can be achieved by creating a timeless design that will withstand the influence of fashion. Personalization of a product can increase its emotional value [14], and thereby prolong its lifespan. From a functional perspective, the product should be a wearable garment that is not obtrusive or hindering in daily activities.

On the material level, this means that the 3D Printed textile should on one hand be suitable for use in garments, and thereby withstand a number of technical requirements, such as flexibility, tear resistance, breathability and water resistance. On the other hand, there are 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.

In this case, a more abstract vision was desired, in order to go beyond the initial findings. The materials experience was formulated as the following statement: 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.

3.3. Manifesting materials experience patterns

According to the steps of the MDD method, the vision that was created in the previous step should be further analysed to obtain materials experience patterns [9]. These are obtained by analysing the vision and proposed interaction to distill 'meanings', which in turn can be translated into material properties by applying the Meaning Driven Material Selection (MDMS) method (see [15] for the application of the method).

The meanings were distilled by means of analysing the metaphor and several brainstorm sessions. The two meanings that were thought to best fit the intended interaction were *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.

The meanings were translated to material properties by analysing them with the MDMS research. In this research, a number of participants was asked to find a material that fits a meaning, to provide an image of it (embodied in a product) and to rate it on a scale of a number of sensorial properties. 13 participants responded for the meaning *intriguing*, and 13 for the meaning *familiar*.

The results of the MDMS research are clustered per meaning in Fig. 3 and Fig. 4. *Intriguing* materials were found to be *surprising* and *unexpected*, by having a different look than feel for instance. They were found to be *playful* and raise curiosity, versatile in their properties and pleasurable to feel. Selected products in which the materials were embodied were practical and functional, but were enhanced by the used material to make them more special and not standard.

Familiar materials were found to be as expected and common. They are considered reliable, and have an air of nostalgia. Most of the selected materials were natural, and recognizable as such. They were embodied in functional, practical products that appeared archetypical for their category.

As seen by the descriptions, certain aspects of the materials are contradicting (e.g. surprising versus expected), and some supplement each other (e.g. warm versus comfortable). Therefore, 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. It is however important to understand how the meanings can be used to enhance and limit each other.

It was decided that the interaction should be *intriguing* at first; by exploring and using the material it will become familiar and personal. This means that the material should be playful, unexpected, raise curiosity and invite 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.

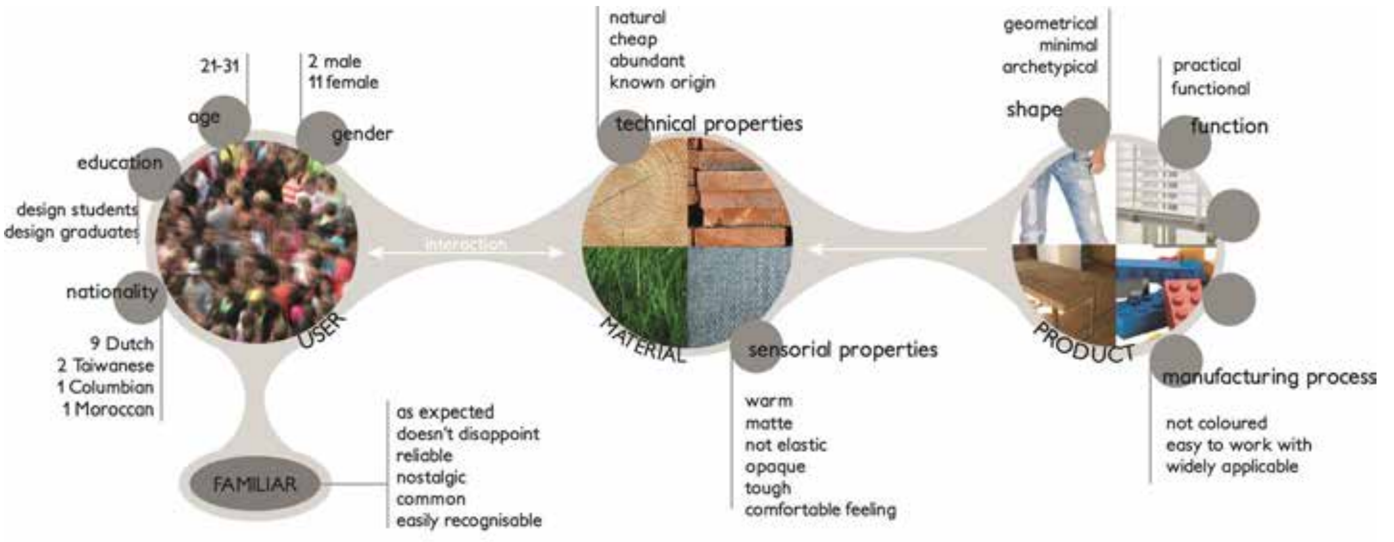


Figure 3. MoM of *familiar* materials

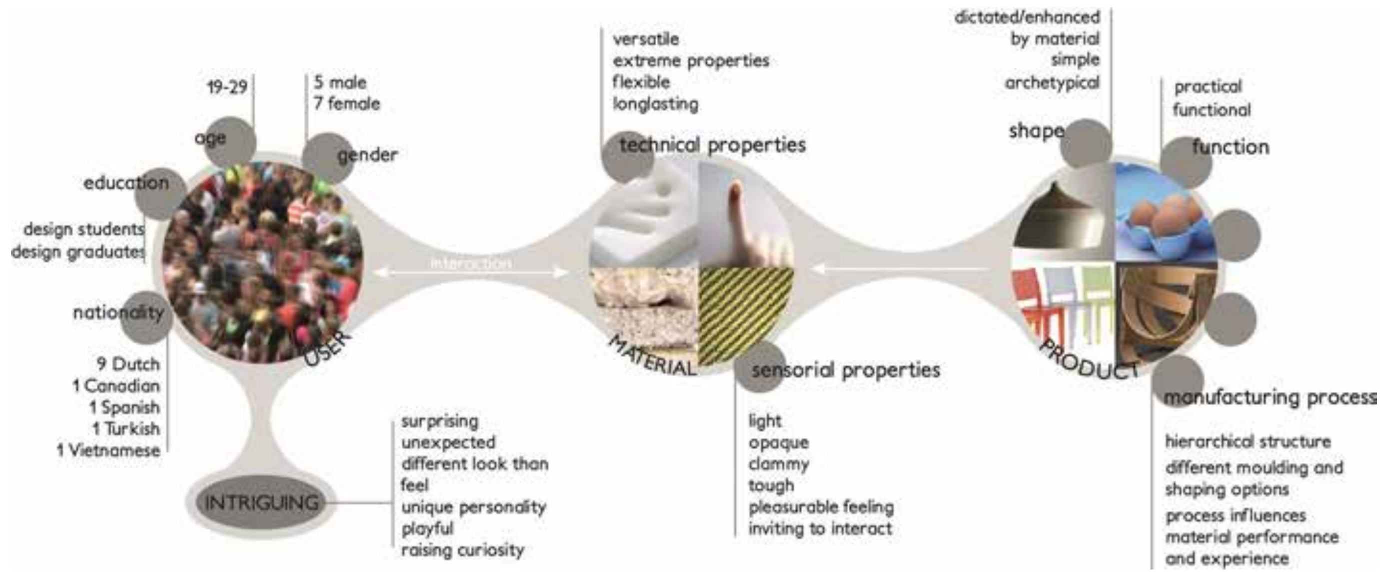


Figure 4. MoM of *intriguing* materials

3.4. Designing material/product concepts

In the final step, the findings from the previous steps should be used to create material and product concepts. With the material requirements and the findings from the technical and experiential analysis in mind, a number of different MSP samples were created. One MSP seemed to be most promising to be used as a textile-like material, shown in Fig. 5. This was chosen to be used in the product concept creation.

a) MSP development

For the concept creation, two workshops were conducted, one with 13 students of fashion design and one with 12 students of industrial design. The ideas that arose from these workshops were analysed. It was found that the students did not regard the 3D Printed material as a textile; it was rather seen as a substitute for plastic parts that are normally rigid and solid (e.g. casts or braces). This led to the conclusion that for this MSP the structure and process were suitable, but the material was not: although the material (plastic) was familiar, it was not familiar for the context it was intended for. After all, although a lot of textiles are made of plastics, their structure prevents it from being recognized as a plastic.

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 Materials Experience Vision was a mixture of cellulose fibers with a flexible acrylic, as shown in Fig. 6. This mixture can be printed using the AM technology Material Extrusion, in which the material is extruded through a (non-heated) syringe in the desired structure, after which it has to dry. The experiments were perfomed both by manually extruding the material through a syringe, as well as by mounting the syringe on a material extrusion printer Ultimaker Original. These initial experiments served as a proof of concept for the newly developed material, although more research is necessary in order to make it suitable for processing. However, the results do give an impression of what the material could be like in the future.

b) Product concept

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. The structure can be varied with: it can have a square configuration or a hexagonal configuration, changing the appearance and openness of the material. It is also very suitable to make alterations in properties (i.e. making the pattern smaller and higher decreases the flexibility of the material), it makes sense to use it for applications where this quality could be used to the fullest. The product should fit in the category garments, as was part of the assignment. By means of several brainstorm sessions, the most valuable product direction was found to be brassieres. These contain a large number of different parts and functions, therefore they are extremely suitable to locally vary material properties and to integrate parts. The design is shown in Fig. 8. The choice was made to design a corselet, which is essentially a cross between a bra and a top, in order to demonstrate the versatility of the selected MSP.

In the concept, the entire product is 3D Printed exactly to the size of the user and can be 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. It is printed at once, meaning there is no need for assembly. This also means that the MSP should fulfill all functions that are usually provided for by a number of different parts and materials.

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 (~0.4 mm) and have a larger pattern size, which makes them softer and more pliant.

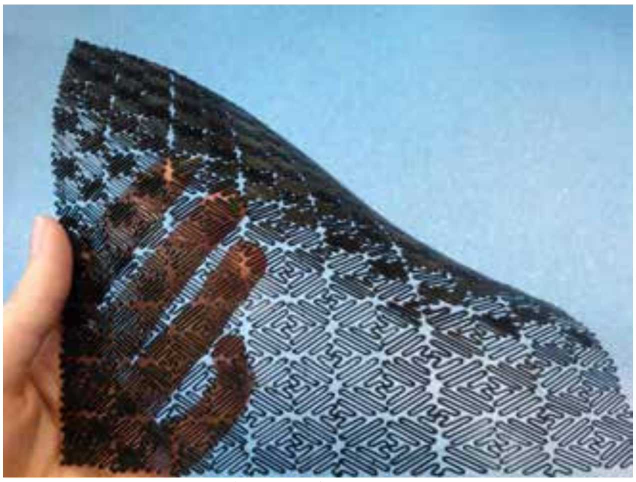


Figure 5. Chosen MSP

Figure 6. Sample of cellulose fibers mixed with flexible acrylic

Figure 7. Prototype of final design

c) Prototype

A prototype of the design was built to test the application of the MSP, as shown in Fig. 7. A dress form was made, to which the product was fitted. It was printed on a material extrusion printer Ultimaker 2 using the material polylactic acid (PLA), which currently produces the most reliable results on this 3D Printer. It was found that the property gradients in the material worked well, although they could have been a little more pronounced by increasing the z-height. The smoothness of the underside of the MSP increased the skin comfort, although some of the edges were still rather sharp.

d) Life Cycle Analysis

The fact that 3D Printing significantly reduces the number of process steps necessary to produce garments 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) (as explained in [16]), and compared to traditional manufactured textiles for 1 kg of textile. It was assumed that the 3D Printed textile was produced by the Fused Deposition Modelling (FDM) process of PLA. The results of the anaylsis, as shown in Fig. 9, were compared to those of traditional textiles, as analysed in [17]. 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. 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%).

4. Discussion

This paper has shown the application of an MDD method to a design process where AM is the primary production method. The goal of the design project was to create a menaingful 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. 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 whole 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 this has not been done before.

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.

The MSP and product that are created as a result of this process, demonstrate the potential for 3D Printed textiles. Even though the final material does not adhere to all the properties that are desirable for textiles, it has shown potential to be used as a 3D Printed textile for garments. Two main factors that should be improved before it can actually be worn are its tear-resistance and the softness of the material, which is necessary if it is supposed to be worn close to the skin. The latter can be improved by either using a more compressible material or a material with a softer outer surface, such as the proposed cellulose material.

The material as it is designed now is bound by current technological limitations. With improvements of current technologies, some advancements for the material can also be made, it would for instance be interesting to test the behaviour

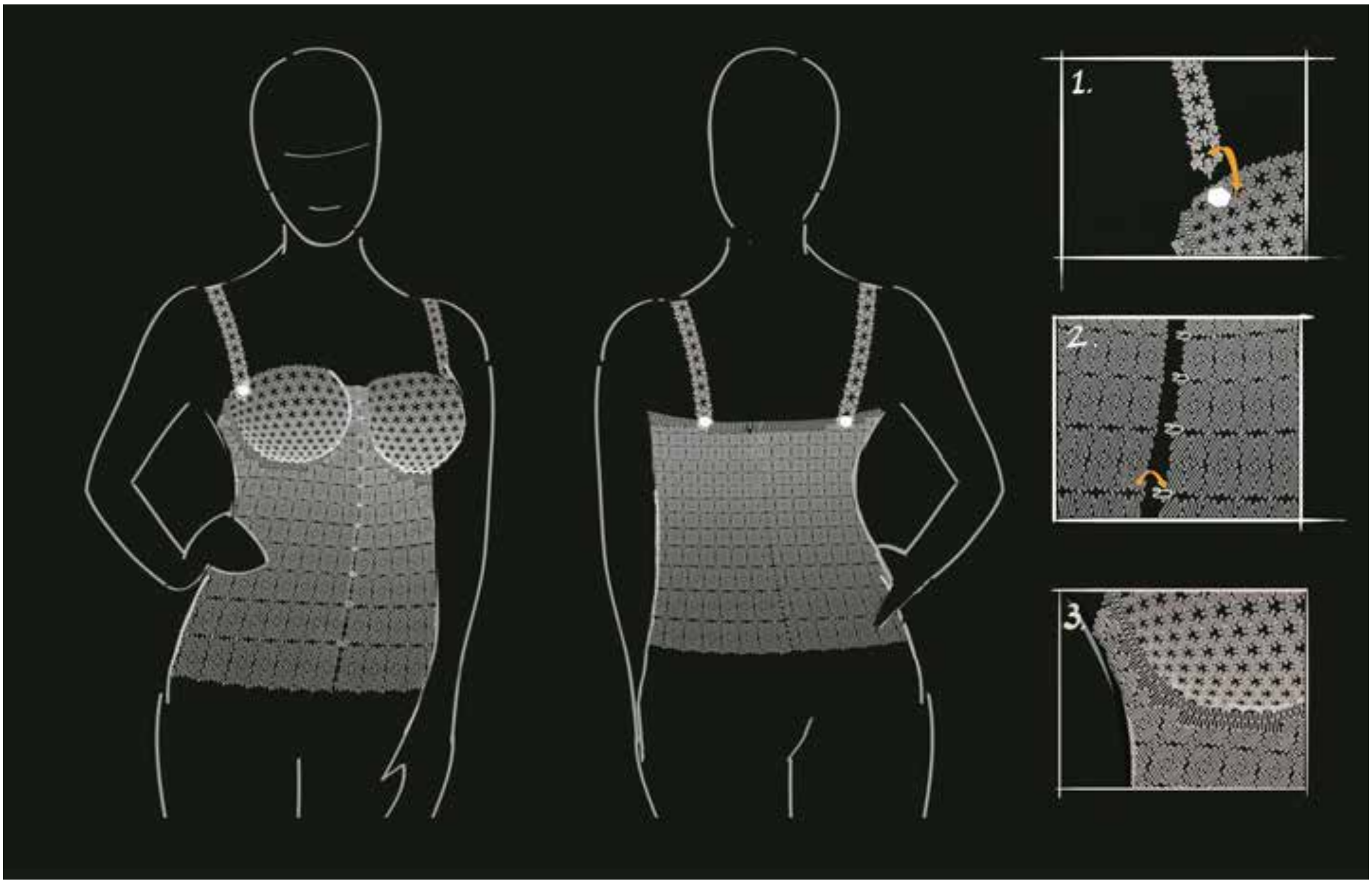


Figure 8. Final design

of the material if the scale of the macro-structure can be decreased, to make it more resemblant of traditional textiles. The current material options were also found to be too limiting, which is why a new material blend was proposed. Although this blend has the potential to be printed, it would be interesting to see different possibilities for printing natural-based materials in the future.

Therefore, for future applications for 3D Printed textiles, it is recommended that an AM process will be developed specifically to create textiles, rather than keep the focus on material development. In essence, textiles should be seen as an MSP: their properties are influenced by materials, structures

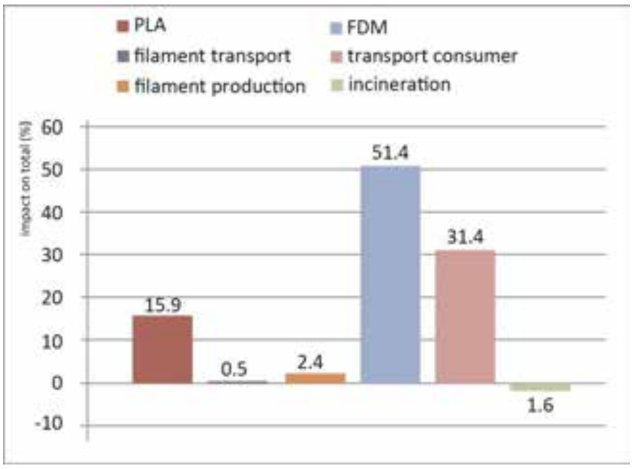


Figure 9. Results of the LCA analysis: impact of each stage of the life cycle of the product as percentage of total impact

and AM processes. In order to be able to print textile-like materials, the materials, structures and process that are in place now should be thoroughly analysed and used as inspiration for new AM processes.

Future work will first be focusing on testing the functionality of the MSP by means of the prototype. Next to that, the cellulose blend will need to be researched further in order to develop it for use in AM and for its function as a textile.

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