



Graduation Master Thesis

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Reversible 3D printing onto textiles for footwear design

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April 22nd, 2022



Submission date
April 15th, 2022

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Abstract

3D printing is currently blooming in a lot of different industries, including fashion in the form of 3D printing onto textiles. In parallel, fashion circularity is an increasing movement that has emerged due to the negative impact that fashion creates on the life on this planet and the planet itself. Therefore, a shift to responsible consumption and production methods (sustainable development goal 12) is necessary. To join this circularity movement, 3D printing onto textiles for fashion is required to fulfil certain requirements, including recycling. However, recycling is nowadays hindered by the lack of methods to separate the 3D printed structures from the textile at the End of Life (EoL). This graduation project researches the possibilities to achieve material separation at the EoL, so that the materials can be independently recycled and turned into new products.

The contribution of this research is a framework to achieve material separation that enables recycling for interfaces created by 3D printing onto textiles. This framework has three key steps, which are: developing a separation plan, selecting materials and designing the polymer-textile connection. The separation happens through heat deformation and more specifically, through increasing the temperature locally during separation. The selected materials are PLA, as the polymer, and plain-woven cotton, as the textile. The printing method used is Fused Deposition Modelling (FDM). The connection design is implemented on a product application, which is a footwear's mid-sole bond to the upper shoe's textile. Four interface designs are tested on separation conditions related to EoL and a scenario of usage conditions, to investigate the effect of the connection design on separation and thereafter, recycling. At the end of the research, clean material separation between polymer and textile is achieved, which is a promising achievement for reversible 3D printing onto textiles.

Preface

For their contribution to this project, I would like to thank the people who supported me throughout this graduation journey. Firstly, my chair Zjenja for his critical questioning and advice on matters of 3D printing and my mentor Ruud for his detailed feedback and vast knowledge on circularity and adhesion. They both were incredible sources of inspiration. Furthermore, I would like to thank a few people that shared their technical expertise and enthusiasm with me. During the test preparation, Israel Carrete, a material's expert and designer, gave me useful advice and help. Holly McQuillan shared her knowledge on textiles and help me better understand them. Jose Martinez was my advisor on 3D visualisation. Also, I am grateful for the support from the staff at Applied Labs in IDE. Finally, my family and friends who were there for me, during hardships and celebrations.

My personal driver for this project is a vision of a world where humans acknowledge and respect nature. Nature that is wild and beautiful. Textiles and fashion are expressions of our personalities and a medium to connect with nature and therefore are essential to our being.

Dimitra Tsoli
15/04/2022

Glossary

3DP 3D printing	Interface 3D printing within textiles produces an interface, a surface where the two materials, meet and interact.
SDG Sustainable development goal	Adhesion Adhesion is the bonding of one material to another, namely an adhesive to a substrate, due to a variety of possible interactions.
EoL End-of-life	Delamination Delamination is a separation along a plane parallel to a surface (Nijland & Larbi, 2010), as in the separation of the polymer 3D printed layers from a textile substrate.
DfR Design for recycling	
DfD Design for disassembly	
FDM Fused Deposition Modelling	
PLA Polylactic Acid	
ABS Acrylonitrile Butadiene Styrene	
PET Polyester polyethylene terephthalate	

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1. *Introduction*



Figure 1. "Active Shoes" by Christophe Guberan, Carlo Clopath and Self-Assembly Lab, MIT.

1.1

3D printing combined with textiles - a step towards circular fashion

Developments in 3D printing (3DP) now offer creative freedom to design innovative structures for fashion products (Lussenburg et al., 2014; Mpofu et al., 2019). 3D printed materials provide textiles with support and create three-dimensional geometry frameworks for shaping the textiles (Kycia, 2018). The engagement of 3DP with fashion is realised mainly into two forms:

(i) 3DP onto textiles (figure 2) - e.g., Foliage Dress by Iris van Herpen, TU Delft and STRATASYS (Doubrovski et al., 2017), “Active Shoes” by Christophe Guberan, Carlo Clopath and Self-Assembly Lab from MIT (figure 1), “Setae” and “Arid Collection” by Julia Koerner and STRATASYS, “Greta Oto Dress” by threeASFOUR, Travis Fitch and STRATASYS and collection by Labelled by - <https://www.labeledby.com/>.

(ii) 3D printed textile structures - e.g., Anthozoa Skirt and Cape by Iris van Herpen, Neri Oxman and STRATASYS, recyclable 3DP sneaker by Zellerfeld and the corselet by (Lussenburg et al., 2014).

In parallel to these technological innovations, the fashion industry has evolved into a new generation where garments are fabricated by low quality material blends to provide affordable clothing, which is quickly discarded. After their first short life, garments are either sold as second-hand fashion, recycled (upcycled or downcycled) or incinerated. Although the international second-hand market is growing, “EPA Clothing and Footwear Waste Estimates” calculated that 36 billion garments are thrown away annually in the US, of which 95% could be reused or recycled (thredUP, 2022). The latest estimation on the textile waste that is recycled into new garments, is less than 1% (Ellen Macarthur Foundation, 2017). Consequently, almost all the material value is lost or downcycled into wiping cloths, carpet padding or insulation. While downcycling extends the life of textiles, it prevents them from being upcycled and used as new garments. Therefore, new virgin materials are essential to produce these garments. This linear system leads to intense material sourcing and material value loss.

Customers and designers have been confronted with the

consequences of fast fashion on the environment. The consequences range from material scarcity, pollution, depletion of natural resources and waste generation (Dissanayake & Weerasinghe, 2021). A transition towards a circular fashion system is now necessary more than ever. In this system, “fashion items are designed, sourced, produced and provided with the intention to be used and circulate responsibly and effectively in society for as long as possible in their most valuable form, and hereafter return safely to the biosphere when no longer of human use” – Anna Brismar, Green Strategy, 2017. In other words, a circular fashion system employs responsible consumption and production methods following the 12th Sustainable Development Goal (SDG 12). Dissanayake & Weerasinghe (2021) identified four aspects of circular fashion: materials, design, consumption and end-of-life (EoL). According to them, in a design context the methods for achieving circular economy are design for: customization, longevity, disassembly, recycling and composting.

Since modern fashion is starting to equip 3DP onto textiles, the products of this encounter need to align with the circular fashion objectives. As mentioned, longevity and recyclability are critical to achieving circular products. Nonetheless, the introduction of polymers and the bonds they form with the textiles complicate the EoL of these products. To enable circular fashion for products created by 3DP onto textiles, the bond between polymer and textile should be both reliable, to ensure longevity during usage, and reversible, to allow for material separation and recycling at the EoL of the product. Reliable bonds between the 3D printed polymer and the textile are insured through incorporating the fabric within the printed material (Doubrovski et al., 2017). By creatively designing the interface between polymer and textile, the designer can achieve separation at the EoL and thus recycling, while maintaining reliable and a long-lasting bond during the product’s life. This graduation project investigates separation possibilities for products that are realised by 3DP onto textiles using Fused Deposition Modelling (FDM), so that at the EoL they can be recycled.



Figure 2. 1 - Foliage dress by Iris van Herpen, TU Delft and Stratasys (Doubrovski et al., 2017), 2 - collection by Labelled by, 3 - “Arid collection” piece by Julia Koerner and Stratasys and 4 - “Setae” by Julia Koerner and Stratasys,

1.2

Material Separation - literature summary and research question

During the past decade, researchers have investigated the adhesion properties of the interface between textile and 3DP polymer (Doubrovski et al., 2017; Gorlachova & Mahltig, 2021; Grimmelsmann et al., 2018; Kozior et al., 2018, 2020; Malengier, Hertleer, Cardon, & Langenhove L, 2018; Meyer et al., 2019; Mpofu et al., 2019; Oyón-Calvo et al., 2019; Sanatgar et al., 2017). Adhesion is crucial for the integrity of the interface and consequently the product's durability and longevity. Parameters that have been studied are derived from the nature of the printing process, the polymer material and the textile material. Amongst these parameters, printing temperature and speed, polymer viscosity and textile pore size attract most attention because of their influence on adhesion.

Therefore, longevity is addressed through the improvement of adhesion. Except longevity, recycling needs to be researched. Currently, the EoL of these products is uncertain, because the material combination cannot be allocated to any of the recycling categories – textile or plastic recycling. The reason is that recycling processes depend on material properties and are designed differently for every single material (Harmsen & Bos, 2020; van Schaik & Reuter, 2014). Therefore, for the case of 3DP onto textiles, material separation, is necessary.

For the materials to be suitable for recycling the separation must happen in a way that they are recovered in good condition. Clean material separation is vital for effective recycling or life prolongment through reusage. However, right now separation is almost impossible to achieve or would require plenty of manual labour, which is not a viable solution. Thus, the knowledge gap that closes the loop of circularity in 3DP within textiles is the material separation.

My scope is to research and test ways to achieve material separation for 3DP textile interfaces. I will identify parameters that allow separation at end-of-life while maintaining a reliable adhesive bond during use and test them at experimental scale as well as in a product prototype. The research question is the following:

“How can we design with 3D printing within textiles in a way that results into durable products during their lifetime and allow for material separation and recovery at the end on their life?”

That question has a dual aim, longevity and separation. Longevity leans towards a reliable, permanent bonds and separation leans towards an adaptive, reversible bonds. Even though they appear contradictory at first sight, they occur at different lifetime stages and are subjected to different conditions. The balance and interaction between these qualities is crucial for reaching circular products. The challenge I will tackle is to maintain longevity while improving material separation. Consequently, the main research question is divided into three sub-questions:

1. Which parameters influence the adhesion between polymer and textile?

2. Which parameters favour separation of polymer and textile that enables reuse or recycling of the original materials?

3. How can we combine the parameters that influence adhesion with the parameters that favour separation in a design, to sufficiently control both adhesion and separation?

The first sub-question is answered through literature research, by reviewing previous research findings to gain an understanding of the adhesion properties and the parameters that regulate it. The outcome of the literature research builds a foundation of the influential parameters that are used in the experimentation through iterative prototyping to shed light on the second sub-question. As for the last sub-question, the previous findings are collectively applied on a footwear product to be tested in regards to adhesion and separation and reflect on the application of both longevity and separation on product scale.

1.3

Design process and readign guide

As a design student, through my learning process I have understood and embraced that design is more than the creation of products. It is the generation of possible solutions to improve the current state of the world. It embodies a vision of a desired future.

This project is approached as experimental research with systematic parameter variation in the context of footwear design. The aim of the research is to gather knowledge through the engagement in iterative prototyping of forms (Faste & Faste, 2011). The desired knowledge here is the circularity potential of products that are created by 3DP within textiles. The iterative prototyping process that leads to this knowledge is printing onto textiles while varying parameters that control adhesion and separation, and afterwards testing their response to separation. The design intention is to create a knowledge foundation about separation and material recovery in the context of 3DP within textiles, so that it can be applied by others in the creation of products.

The report is structured in seven chapters. The opening chapter – current one – is an introduction to the topic. It explains the relevance of the project to the fashion crisis and the emergence of circular fashion, continues with the development of research question and finishes with this reading guide. Next, chapter 2 introduces the desired material journey and analyses the existing system of textile recycling and the role of disassembly as a means for achieving separation.

Keeping in mind the desired material journey, chapter 3 dives into the 3DP onto textiles method and seeks answers to the first sub-question through literature research. To begin with, adhesion for material interfaces is explained, as it defines longevity. Subsequently, the parameters that regulate adhesion are gathered and synthesised to reach conclusions about what parameters are of interest and how they interrelate.

In chapter 4, the learnings of the literature review (chapter 3) are used to perform an experimental research which aims to provide answers to the second sub-question about separation. It includes a method section, a results and discussion section and a section dedicated to conclusions. The learnings from this chapter need to be applied to a product application. Therefore, chapter 5 analyses the design possibilities and through an elimination process selects the product to apply the research, a footwear mid-sole.

After defining the product to apply the separation learnings, we transition to chapter 6. Chapter 6 aims to answer the third and last sub-question by applying explorative prototyping on the interface design of the polymer-textile bond of footwear mid-sole with the upper shoe. Four design variations are tested in two different tests, one that addresses separation at the EoL and one that addresses separation during the product's lifetime. Method, results and conclusions are the contents of this chapter. Finally, chapter 7 is a critical reflection on the project and finishes with future recommendations.



2.1 The envisioned material journey

According to the waste framework directive in the European Union, the waste hierarchy is shown in figure 4. Waste prevention is the number one goal, followed by preparation for reuse, recycling, recovery and disposal. In the context of 3DP onto textiles, waste prevention is achieved as much as possible through longevity. However, the next steps need to be addressed as well. The separation plan proposed in this thesis aims to enable responsible material flow through the system and safe return to the biosphere by focusing on preparation for reuse and recycling.

The material lifecycle that improves circularity while maintaining the directive's instruction for polymer-textile interfaces is explained in figure 5. The journey starts from the renewable resources. From there, two different materials emerge, a polymer and a textile fibre. These materials are used independently to create filament for 3DP and textile accordingly. The two materials are brought together with 3DP and produce a product, which is used by a consumer.

After their first life the materials enter loop 1. In loop 1

a process separates the two materials and results into recyclable bioplastics and textiles. These materials are inserted back to the system at a material and product level accordingly. Loop 1 is repeated as much as possible, until the materials are not suitable for recycling.

When loop 1 reaches its limits, the materials enter loop 2 after usage. Loop 2 is inspired by the butterfly diagram developed by Ellen McArthur foundation. Since both PLA and cotton are renewable resources, they follow the journey back to virgin materials through biochemical feedstock, anaerobic digestion, regeneration biosphere and farming.

In this material journey, recycling – or when possible, reuse – is promoted as much as possible with consideration to the value of the materials and the energy consumed for those processes. That is because, material purity and energy consumption are important factors for effective recycling systems.

Waste Hierarchy

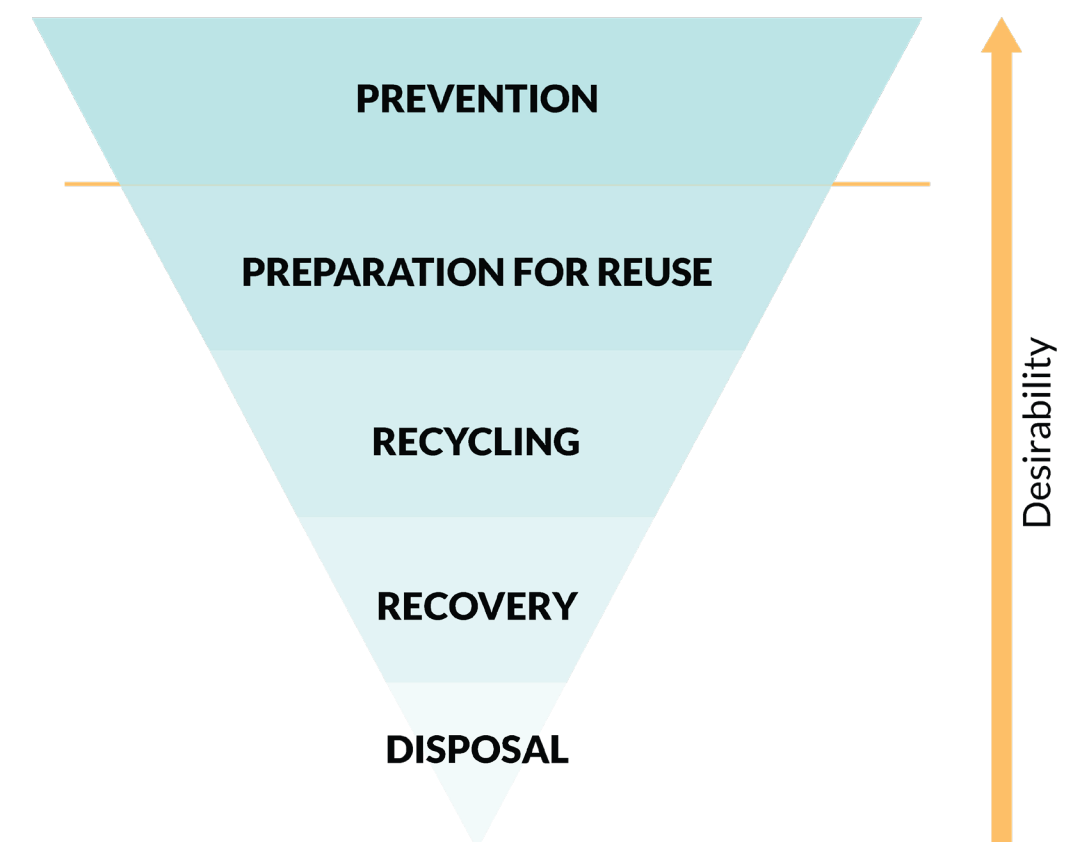


Figure 4. The waste hierarchy according to the waste framework directive by the European Commission.

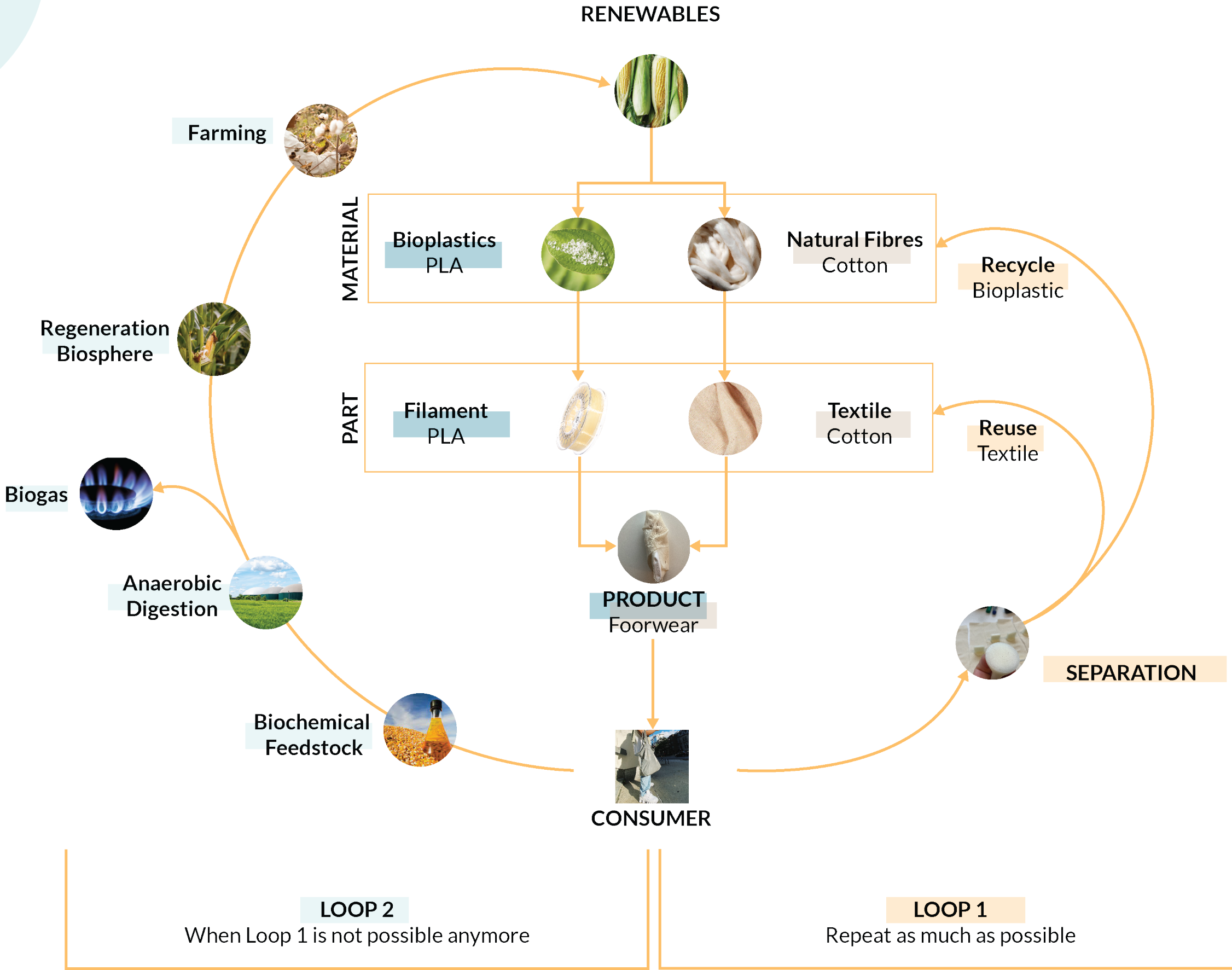


Figure 5. The envisioned material journey.

2.2

The current textile recycling routes and processes

To implement Loop 1, separation must be aligned with the textile recycling routes and process. The current recycling routes for material reuse and recycling in the textile value chain are described by Sandin & Peters (2018). According to them, fabric recycling happens when the fabric of a product is recovered and reused in new products. In the case that the fabric is dissembled without compromising the polymer structure, what happens is fibre recycling. In general, among other routes of textile recycling, fabric or fibre recycling require less energy, in contrast with polymer and monomer recycling, that require more energy to break the material down to smaller building units (Harmsen & Bos, 2020). The recycling routes are shown in figure 6

According to the waste framework directive, in a desirability scale, after long-lasting products and product reuse, fabric recycling is preferable. Regarding the other types of textile recycling, there are different ways to achieve them and oftentimes they happen through the combination of various mechanical, chemical and thermal processes (Sandin & Peters, 2018).

Unfortunately, textile recycling nowadays is problematic. The lack of sorting and separation technologies that would produce fractions pure enough for recycling is currently hindering textile recycling (Östlund et al., 2015). Thus, it is important to design methods for separation. Other than that, the current textile recycling routes are characterised by a lack of infrastructure, low collection rates, manual sorting, low recycling rates and relatively low-value recycled products (Roos et al., 2019). Considering those issues, there is potential to increase recycling rates (Sandin & Peters, 2018) through increasing material separation rates (Roos et al., 2019).

Textile Recycling Routes

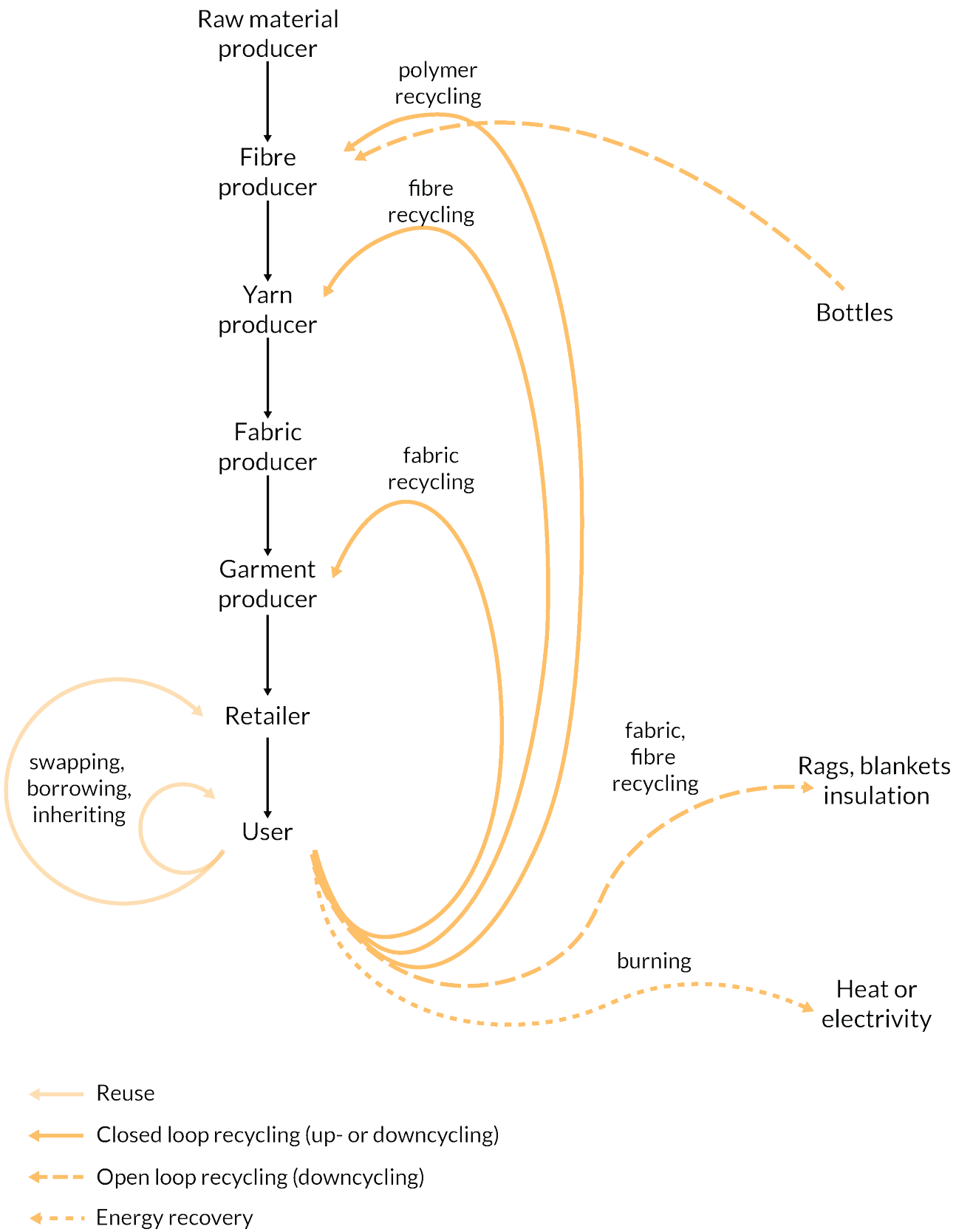


Figure 6. The textile recycling routes, based on the analysis of Sandin & Peters (2018).

2.3

Separation approaches for transitioning to the envisioned material journey

To increase separation rates, a separation method that suits the needs and characteristics of the product is needed. This can be approached as design for disassembly. To design for disassembly is to create products with the intention of minimizing value loss at the end of life (Suffian et al., 2016). For products utilizing the method of 3DP onto textiles, the 3DP materials need to be separated from the textile with minimum value loss.

Design for disassembly has been used in design and architecture to address many types of products including electronics and buildings. However, the approach cannot be directly applied on polymer-textile interfaces, because they differ in their production method, 3D printing, mechanism of connection, and the final product is not a solid artifact. Biodegradable layers, engineered textiles, temperature sensitive fibres, heat deformation of filament and responsiveness to moisture are some methods that could be applied to separate the polymer-textile interfaces (figure 7).

(i) Heat deformation

Heat can cause both polymers and textiles to deform. Regarding polymers for 3DP, they are sensitive to changes in temperature, therefore applying heat during disassembly could reverse the process by softening the polymer and in turn allowing the textile to be detached. About textiles, temperature sensitive fibres react to heat and depending on their fabrication they can expand or compress when subjected to heat or coldness.

(ii) Biodegradable Layers

One potential solution to achieve separation and thus improve circularity, would be to employ biodegradable layers as one of the materials (e.g., the textile) or as additional layers between the materials. The biodegradable layers would engage with the materials and once optimum circumstances are reached, they would biodegrade and release the materials to follow their own recycling path.

(iii) Engineered stretchability in textiles

This mechanism could be applied to polymer-textile interfaces if the two stages of stretchability would be to engage the polymer into the textile during usage and to release the polymer from the textile at the EoL by fabricating the textile in a certain way.

(iv) Moisture responsiveness

Similarly with heat, textiles respond to moisture changes in the environment. Scott (2013) fabricated textiles that based on the moisture in the environment change forms. This could be a potential solution to for a disassembly lead by textile deformation.

To conclude, in order to apply active disassembly based on textile properties, such as heat sensitive fibres, engineered stretchability and moisture responsiveness needs textile fabrication expertise and specialised machinery. Biodegrading layers largely depend on time and decomposition rate, which is challenging to operate without having biology expertise. Therefore, heat deformation for polymers is the most approachable solution in comparison with the other methods discussed and can be implemented using common materials and processes.

To provide a general disassembly/separation framework, Chan et al. (2016) have named ten key principles on how to design for disassembly, from which three principles that are most relatable to this research. Following, these principles are discussed in the context of 3D printing within textiles.

1. Having a disassembly plan.

It is crucial to have formulated a methodology on how to connect and at the same time safely separate the materials after their usage phase, so they can continue their journeys independently in a way that it fits the existing infrastructure.

2. Selecting the materials.

The selected materials define the recycling potential and impact the disassembly methodology. Therefore, the textile and polymer choice require special attention.

3. Designing the connection

Connection details are considered to be part of the production method. For example, the contact surface between polymer and textile and the extend of the textile fibre embedding in the printed part are some of the parameters that influence the connection.

In this chapter the focus is on the disassembly plan, which is explained in sub-chapter 2.1. The material selection and connection design will be explored in literature research and tested in the experimental research chapters.

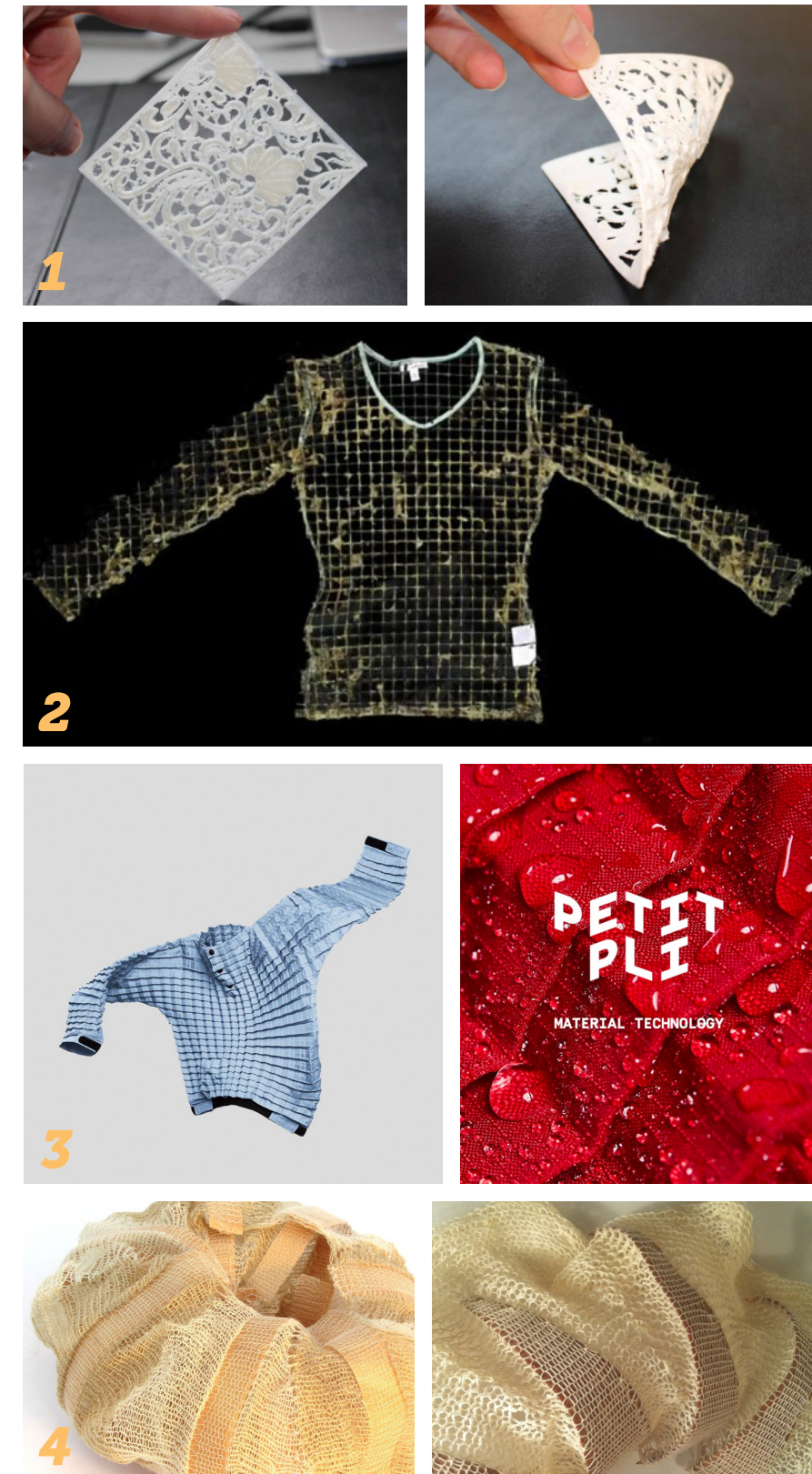


Figure 7. 1 - Heat deformation of a polymer, image and inspiration by (Melnikova et al., 2014), 2 - Research done by New Zealand Merino Company (NZM) about the biodegradability of merino wool, 3 - Engineered stretchability in textiles, image and inspiration by "Petit Pli" - <https://shop.petitpli.com/> and 4 - Moisture responsiveness of textiles, image and inspiration by (Scott, 2013).

3.1

The role of adhesion in 3D printing onto textiles

Adhesion is defined as the attraction between two dissimilar phases or as the bonding of one material to another, namely an adhesive to a substrate, due to a variety of possible interactions. The types of adhesion are: mechanical interlocking, physical bonding and chemical bonding. Mechanical interlocking occurs when two materials are held together mechanically because the viscous adhesive material (deposited material) flows into the voids of the adherend surface (substrate) or around projections on the surface (Pike, 2021). Physical bonding is always present and happens due to van der Waals forces. In comparison to mechanical interlocking and chemical bonding, physical bonding is characterised by weak attraction forces, that can be considerable on large contact surfaces. Chemical bonding includes covalent, ionic and metallic bonding and is responsible for cohesive forces, that occur inside the adhesive material itself. This type of bond is uncommon between dissimilar materials. These three types of adhesion can occur one-by-one, or more than one simultaneously.

Singha (2012) argues that strong adhesion is a matter of impurities presence, material compatibility (wetting), fibre surface (roughness) and the process (viscosity). The presence of impurities on the substrate negatively affects adhesion. Wettability of the substrate is the ability of a liquid to maintain contact with a solid surface and it is controlled by the balance between the adhesive and cohesive interaction (Moldoveanu & David, 2017). Wettability is measured by the contact angle and good wettability results in larger contact area. Another substrate characteristic that affects the adhesion quality is roughness. Roughness creates possibilities for mechanical interlocking

to occur and increases the surface for physical adhesion. The substrate roughness should be in accordance with wettability, to prevent voids (due to high roughness) where adhesive cannot reach (due to low wettability). Last but not least, a factor that is defined by the adhesive is viscosity. Low viscosity is important to ensure that the adhesive flows through the substrate and penetrates the voids.

In the context of 3DP onto textiles, mechanical interlocking is the most observed adhesion type (Awaja et al., 2009; Grimmelsmann et al., 2018; Mpofu et al., 2019; Pei et al., 2015). In that case, polymer is the adhesive or deposited material, textile is the adherent surface or substrate and its roughness and pores constitute the voids where the adhesive flows through (figures 9-10). Physical bonding is always present as mentioned, and cohesive bonds, thus chemical bonding, are created between the 3D printed polymer layers (figure 10).

According to Wypych (2018), the parameters that define interlocking are the shape, size and frequency of the textile pores, roughness and thickness of the textile substrate and the viscosity of the deposited material on the bonding surface. For the polymer adhesive to wet the substrate, it needs to have a suitable viscosity and surface free energy, while the textile substrate needs to have a suitable surface free energy to allow the adhesive to spread. Viscosity and surface free energy are influenced by different parameters, such as the printing process, and the polymer characteristics and the textile characteristics, accordingly. In figure 11 the relations between adhesion and the variables (independent and dependent) are shown.

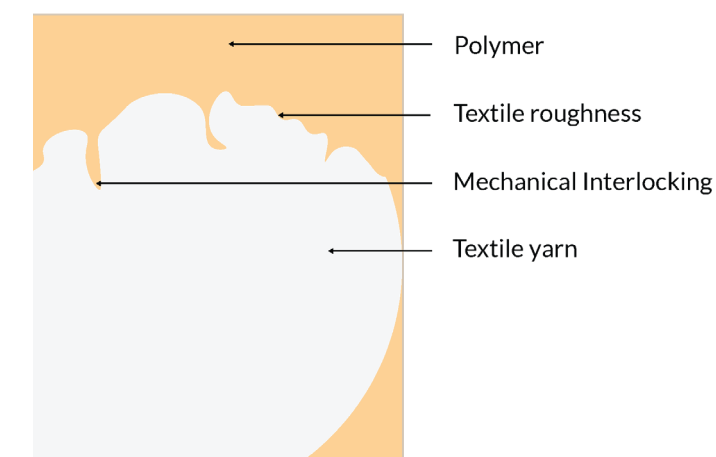


Figure 9. Zoom in – Mechanical interlocking between textile substrate and polymer adhesive.

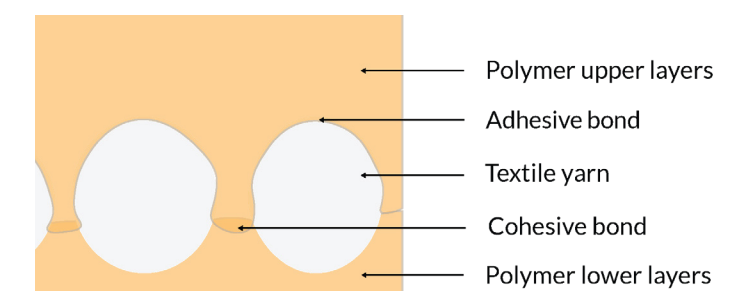


Figure 10. Zoom out – The adhesion types between textile substrate and polymer adhesive.

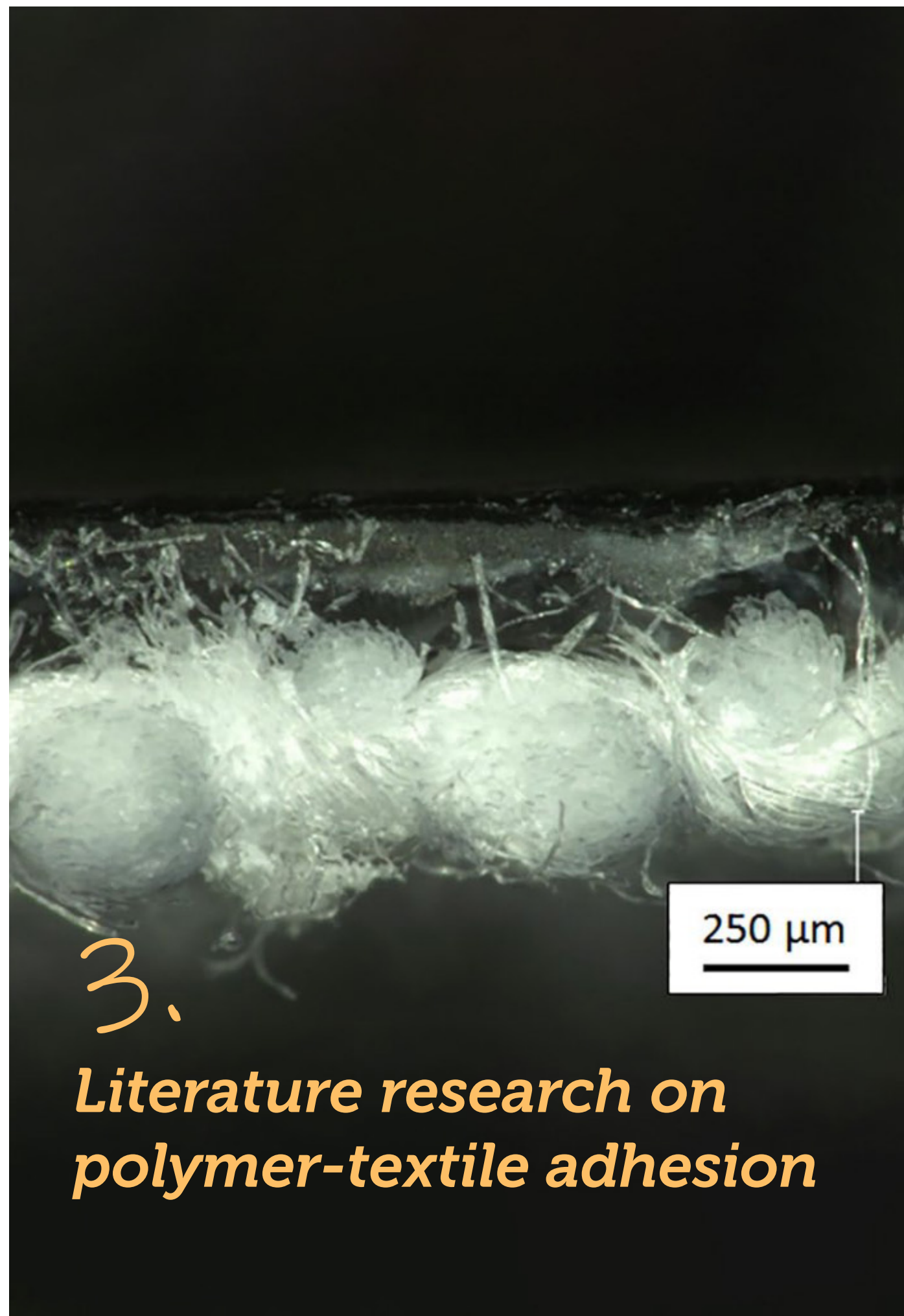


Figure 8. Microscopic image of the cross section of PLA 3D printed on linen (Meyer et al., 2019).

Parameter Relations

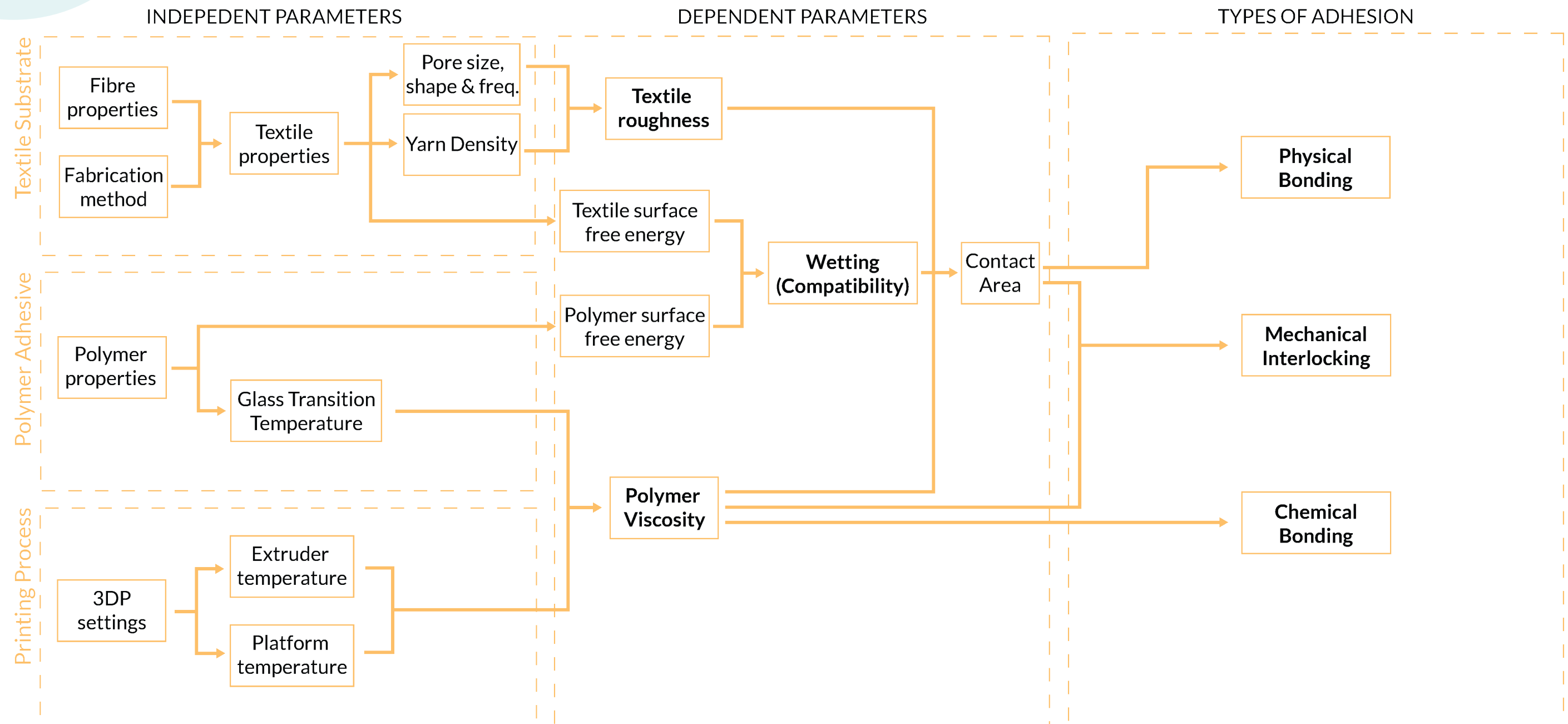


Figure 11. The connections and dependencies between 3d printing process, polymer and textile related parameters in the context of adhesion.

3.2

Parameter analysis

3.2.1 Printing Technique & Settings

The printing technique that has been used by the vast majority of the research for 3DP onto textiles is Fused Deposition Modelling - FDM (Doubrovski et al., 2017; Gorlachova & Mahltig, 2021; Grimmelsmann et al., 2018; Loh et al., 2021; Lussenburg et al., 2014; Malengier, Hertleer, Cardon, & Langenhove, 2018; Mpofu et al., 2019; Oyón-Calvo et al., 2019; Pei et al., 2015, 2017; Rivera et al., 2017; Sabantina et al., 2015; Sanatgar et al., 2017; Spahiu et al., 2017). Kozior et al. (2020) specifically states that no other 3DP technologies have been used than FDM for this purpose. The reasons for this choice are the inexpensiveness and accessibility of FDM technology, the suitability for the desired performance and the applicability on the textile substrate. FDM technology uses polymer filaments that are melted and deposited on a printing bed through an extruder nozzle. Each layer is deposited on the previous one by lowering the printing bed (Novakova-Marcincinova et al., 2012).

Pei et al. (2015) explain the process of 3DP polymers directly on fabrics. However, when talking about 3DP onto (within) textiles in this project, we refer to a slightly different approach, where the textile is placed on the

print bed after the printer has already deposited some layers of material on (figure 12), based on the research of Doubrovski et al. (2017) and similarly to the research of Loh et al. (2021). This approach has proven to overcome problems of adhesion between the fabric and the 3D printed material, resulting in a more reliable bond (Doubrovski et al., 2017). The result of this process is a material interface, constructed from polymer and textile.

After having established a printing technique, the further factors that should be evaluated are the print settings. Print settings do not only greatly impact the visual and haptic finishing of the printed structure (Pei et al., 2015), but also the adhesion of the same structure. Existing research shows that printing temperature (extruder temperature) and printing speed have the greatest impact on polymer-textile adhesion (Sanatgar et al., 2017). It should be clear, that most past research is revolving around printing on fabrics and not onto, so there might be parameters where the two methods deviate, such as the textile thickness.

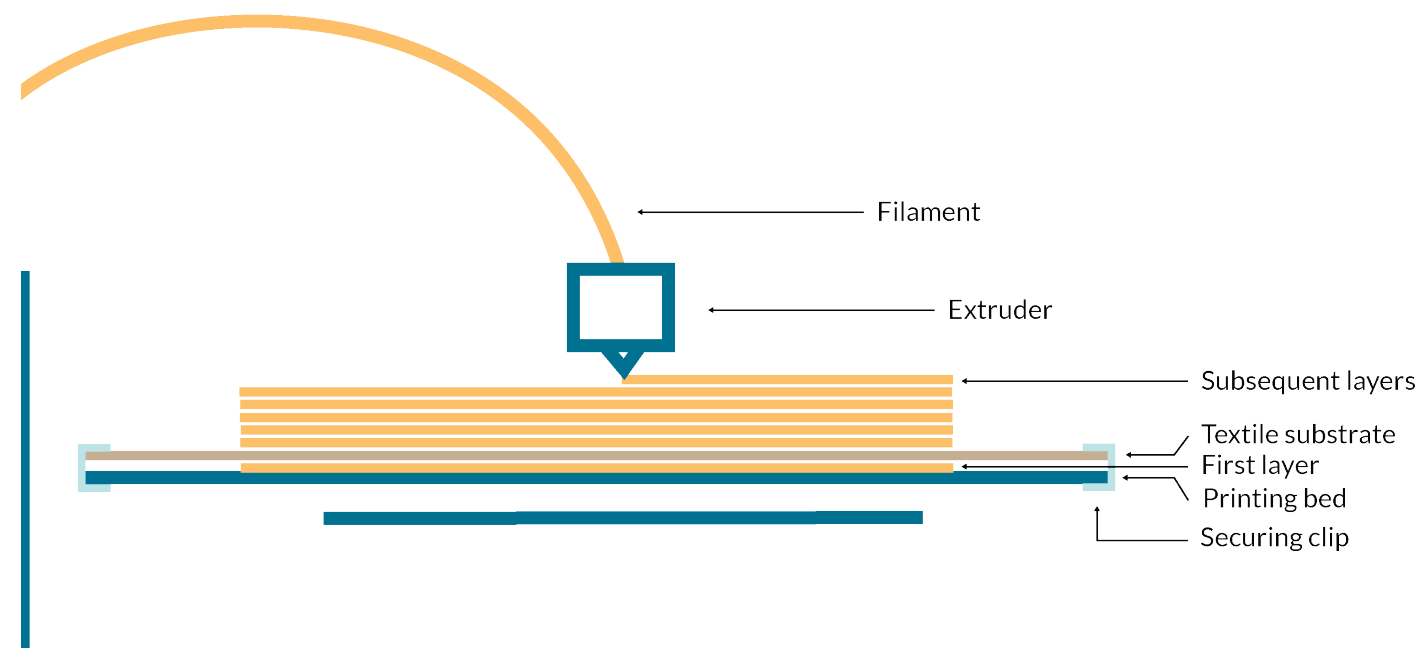


Figure 12. The process of 3D printing onto textiles.

Printing Temperature & Platform temperature

Higher process temperatures lead to increased adhesion of 3D printed structures and textiles (Gorlachova & Mahltig, 2021; Rivera et al., 2017; Sanatgar et al., 2017; Spahiu et al., 2017). That is attributed to the fact that high temperatures lead to more fluid polymers, so reduced polymer viscosity, consequently allowing penetration into the textile's pores (Gorlachova & Mahltig, 2021; Rivera et al., 2017; Spahiu et al., 2017), enhancing mechanical interlocking. Extruder or printing temperature is the temperature that the polymer comes out from the nozzle and platform temperature is the temperature of the printing bed. In figure 13 it can be seen how the platform temperature and the change in viscosity influence adherence. The printing temperature cannot be indefinitely increased, because of the thermal stability of polymers and textiles. In their research, Gorlachova & Mahltig (2021) found that increasing either of the temperatures, decreases viscosity and thus increases the adhesive bonds. Generally, it is suggested to use temperature settings significantly below the polymer's decomposition temperature. The platform temperature should be the manufacturer's suggestion, but the printing temperature is advised to be 5 to 10°C higher than the average temperatures recommended by suppliers (Loh et al., 2021).

Printing Speed

Another setting that is studied is printing speed and especially for the layers closely to the interface. Decrease of the print speed can potentially give time to the polymer to flow through the pores of the fabric and achieve better adhesion. Gorlachova & Mahltig (2021) found that adhesion is linearly decreased with the elevation of the first layer's (or the layer that is in contact with the interface) printing speed. They conclude that moderately slow speeds are strongly suggested for printing the layers in contact with the interface.

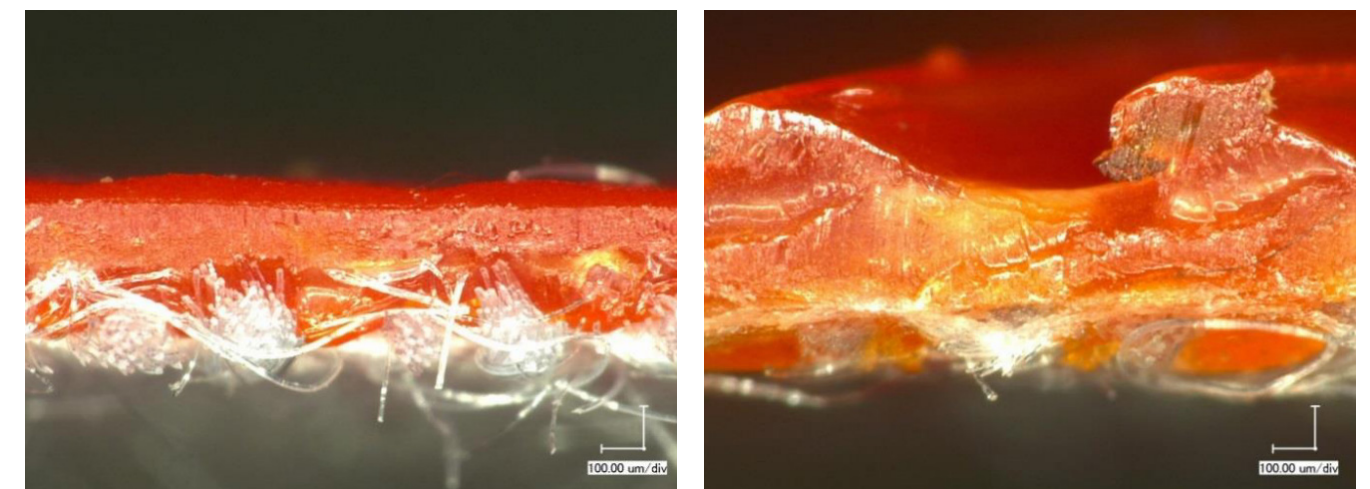


Figure 13. Cross section of PLA's penetration into polyester woven textile at printing bed temperatures of 20°C (left) and 100°C (right) (Spahiu et al., 2017).

3.2.2 Polymer Properties

The most relevant polymer properties are the glass transition temperature (melting point of the polymer), surface free energy that defines wetting and last but not least, viscosity. The commonly used materials in 3DP are PLA and PA 6.6 (Nylon), because of their accessibility and performance in regards to physical adhesion on textile fabrics (Grimmelsmann et al., 2018). Their thermal properties and suggested temperatures for printing (extruder and platform) are given in table 1.

Melt flow index is a measure of the resistance to flow (viscosity) of the polymer melt at a given temperature under a given force for a predetermined period of time (Riley, 2012). Polymer viscosity, is a dependent polymer parameter. Viscosity is largely depending on temperature and thus influenced by the printing settings (printing and platform temperatures). Higher printing temperature leads to lower viscosity, which allows deeper and stronger material penetration of polymers into fabrics (Spahiu et al.,

2017). The platform temperature prolongs the time when the polymer is at low viscosity and consequently enhances penetration. This penetration results into form-locking connections and potentially wetting (Kozior et al., 2020).

From table 1, it seems that Nylon has lower viscosity, which favourable for adhesion. Additionally, Gorlachova & Mahltig, (2021) support that Nylon is less hydrophobic than PLA, meaning that it has higher surface free energy and is more suitable for wetting. Nonetheless, PLA is more sustainable, as it derives from renewable resources and is biodegradable. Furthermore, Pei et al. (2015) performed a comparative analysis between the polymers and found that PLA is considered the best fitted for 3DP with textiles due to printing quality reasons – low warping and stringing properties (Loh et al., 2021). To conclude, Nylon is better fitted for adhesion, but PLA is more sustainable and produces better quality results.

Table 1: Thermal properties for PLA and Nylon.

Property	PLA	Nylon	Reference
Glass transition temperature	60 oC	50 oC	Ultimaker (https://support.ultimaker.com/hc/en-us)
Melting temperature	145 - 160 °C	185 - 195 °C	
Melt mass flow rate	6.09 g/10 min (210 °C, 2.16 kg)	6.2 g/10 min (250 °C, 1.2 kg)	
Printing temperature	200-210 °C	230 - 260 °C	
Platform Temperature	60 °C	60 - 70 °C	

3.2.3 Textile Properties

Pore shape, size and frequency, textile roughness and textile surface free energy are the most relevant textile parameters regarding adhesion. These parameters are regulated by the fibre properties and the textile fabrication method (e.g., weaving or knitting). Figure 14, shows the composition of textiles, from fibre to yarn and textile.

The fibre dimensions that derive from the fibres' origin and structure are three; fineness (linear density), length and density. Fineness determines flexibility, length coherence and density weight of the fabric. Meyer et al. (2019) indicate that large fibre lengths increase the fibre-fibre friction and therefore textile cohesion. Yarns can be fabricated into textiles with different methods. The most common fabrication methods for textiles are weaving and knitting, which create fabrics with very different qualities. Woven textiles are tighter, easier to sew, but crease easily (Pei et al., 2015), while knitted textiles have less dimensional stability and thus can be stretched along their width.

For polymer-textile adhesion roughness characterisation happens at two levels. The spinning of the fibres defines the yarn density, which is the first level of textile roughness (voids between fibres). Thus, yarn density affects adhesion properties of polymer-textile interfaces (Meyer et al., 2019; Sanatgar et al., 2017). The fabrication of the textile defines the textile pores, which is the second level of roughness (voids between yarns). Pore size is defined by the tightness or looseness of the fabrication method. Tightly fabricated textiles have smaller sized pores and loosely fabricated textiles have larger sized pores. Pore size is proven to have key influence on the 3DP within textiles process. Generally, it can be challenging to achieve attachment if the substrate's pores size or volume offer limited surface area, especially for the bottom layers, which are less likely to adhere on the textile (Rivera et al., 2017). This means that large textile pores favour the polymer flow and therefore adherence (Grimmelsmann et al., 2018; Sabantina et al., 2015) through mechanical interlocking (Sabantina et al., 2015). Roughness at both levels increases the surface area, and consequently physical adhesion, and is the reason that mechanical interlocking occurs (Awaja et al., 2009; Mpofu et al., 2019; Pei et al., 2015).

Free-standing fibres are directly related with textile roughness, and their presence increases the contact area and the mechanical interlocking between polymers and textile (Mpofu et al., 2019). On the other hand, surface impurities decrease the surface free energy and reduce adhesion. Removing these impurities by washing can increase attachment and therefore decrease the contact angle (Gorlachova & Mahltig, 2021).

Textiles with larger thickness have been found to perform better and achieve stronger adhesion (Gorlachova & Mahltig, 2021; Grimmelsmann et al., 2018; Kozior et

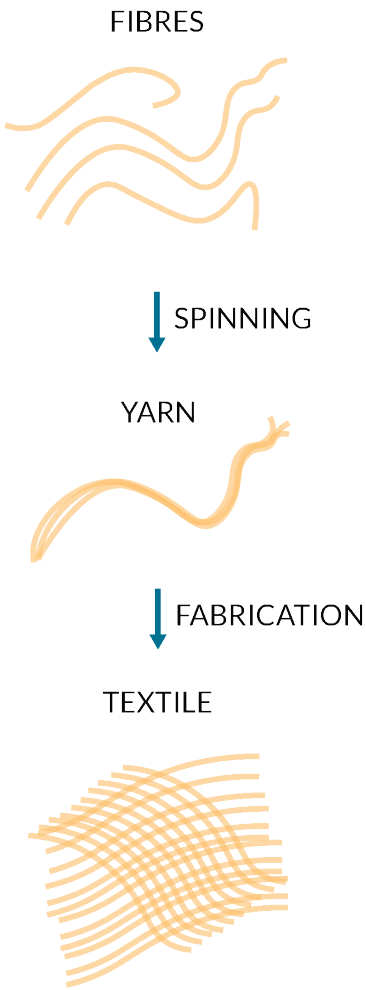


Figure 14. Composition of textiles: Fibres are raw material which is being spun or twisted together to make yarns. Yarns are interlaced, interloped or bonded together in different ways to produce textiles.

al., 2020; Mpofu et al., 2019). This could potentially be attributed to the increased connections inside the textile structure, which provide wider surface area for polymer penetration (Meyer et al., 2019; Mpofu et al., 2019) and thus mechanical interlocking connections.

Lastly, surface free energy is determined by the absorption of molecules and its increase contributes to wetting and therefore to the contact area increase. The increase of contact area, increases polymer-textile physical adhesion (Mpofu et al., 2019; Pei et al., 2015). Nonetheless, the surface free energy of the polymer is equally important for wetting and thus adhesion.

3.3

Parameter relations and their influence on adhesion

The parameter division to printing process, polymer and textile, may seem logical, but in reality, all the before mentioned parameters develop connections across different categories. In figure 15 there is an overview of the overlapping categories and their parameters, classified and placed on their assigned location on the “map”. Wetting is the connection link between polymer and textile, due to their surface free energies. Increased surface free energies lead to enhanced wetting and hence enhanced adhesion. The common ground between polymer and 3DP is attributed to the nature of the process, where the polymer is liquified and deposited on the printing bed. Therefore, printing settings such as extruder temperature and platform temperature need to be adjusted in accordance with the glass transition temperature of the polymer and combined, they define the polymer viscosity when it is being deposited on the printing bed. Finally, low printing speed and high platform temperature enhance the polymer penetration into the textile voids that characterise textile roughness.

Responding to the first sub-question, the polymer-textile adhesion is influenced by a variety of parameters, amongst which the most relevant ones are textile roughness – and thus textile pore shape, size and frequency, and yarn density –, temperature related printing settings and polymer glass transition temperature. These parameters are important because they are mostly related to mechanical interlocking. Mechanical interlocking forms adhesive bonds

between different materials (in contrast with chemical bonding), which are stronger than physical bonding .

Nonetheless, mechanical interlocking could restrain material separation at the EoL. Therefore, it is important to test the boundaries of separation in regards to the parameters that influence adhesion. Independent parameters are suitable for testing separation, as they can be varied systematically. Polymer glass transition temperature is tied with the printing temperature, therefore varying only the polymer property could be challenging. On the contrary, printing temperature can be varied to a limited extend to decrease viscosity and allow for deeper penetration. Luckily, this process can be reversed at the EoL, by increasing the temperature locally around the connection and thus decreasing again the polymer viscosity resulting into possible separation. The local temperature increase during separation will be tested in the next chapter. Finally, regarding textile roughness, the parameter that is the easiest to vary systematically is the pore size. This can be achieved by experimenting with a textile from the same fibre and fabrication method resulting into two textiles, each of them having a different pore size. Increased pore size increases textile roughness and consequently adhesion, nevertheless it is important to investigate how it influences separation. For this reason, the next chapter is dedicated to research the influence of increased temperatures and textile roughness on separation.

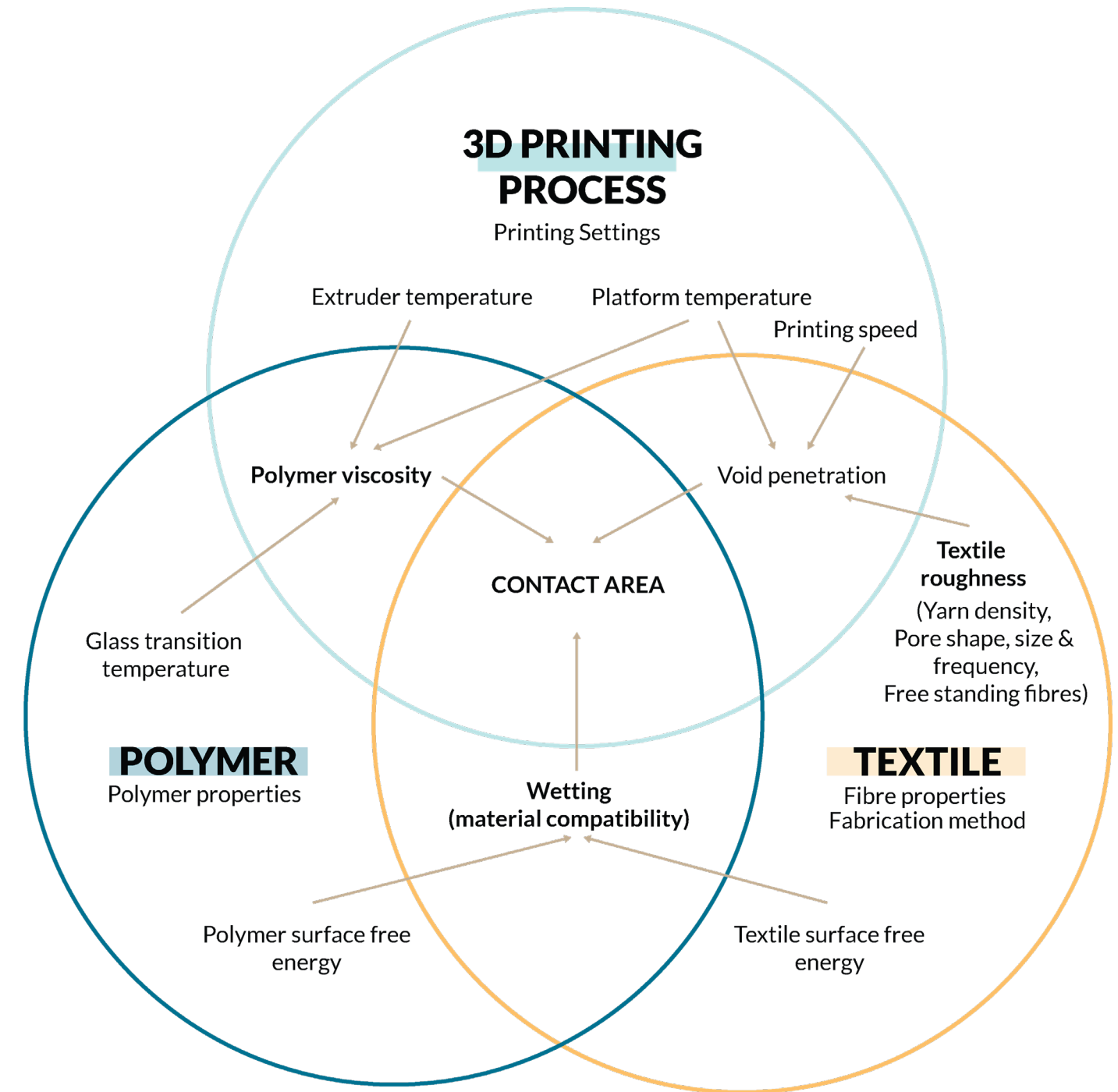


Figure 15. The parameters that influence polymer-textile adhesion are located on the overview based on their belonging to the categories: printing process, polymer and textile. The intersections include dependent parameters that are related to more than one category. Connections amongst the parameters are indicated with arrows. For example, textile surface free energy together with polymer surface free energy influence wetting, that in turn affects the contact area.

4.

Experimental testing on polymer-textile separation

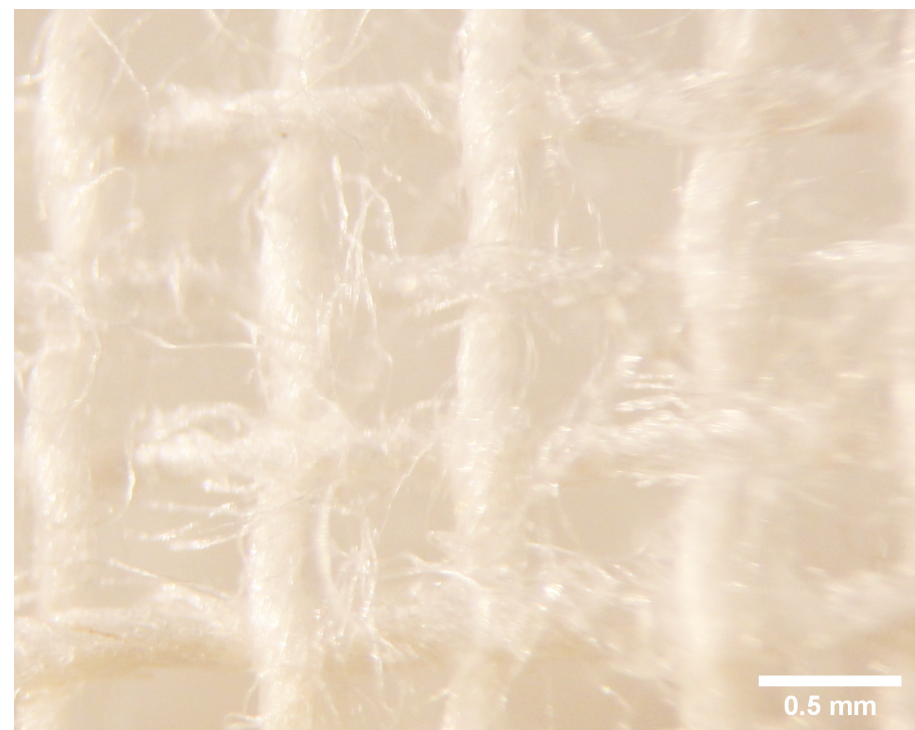
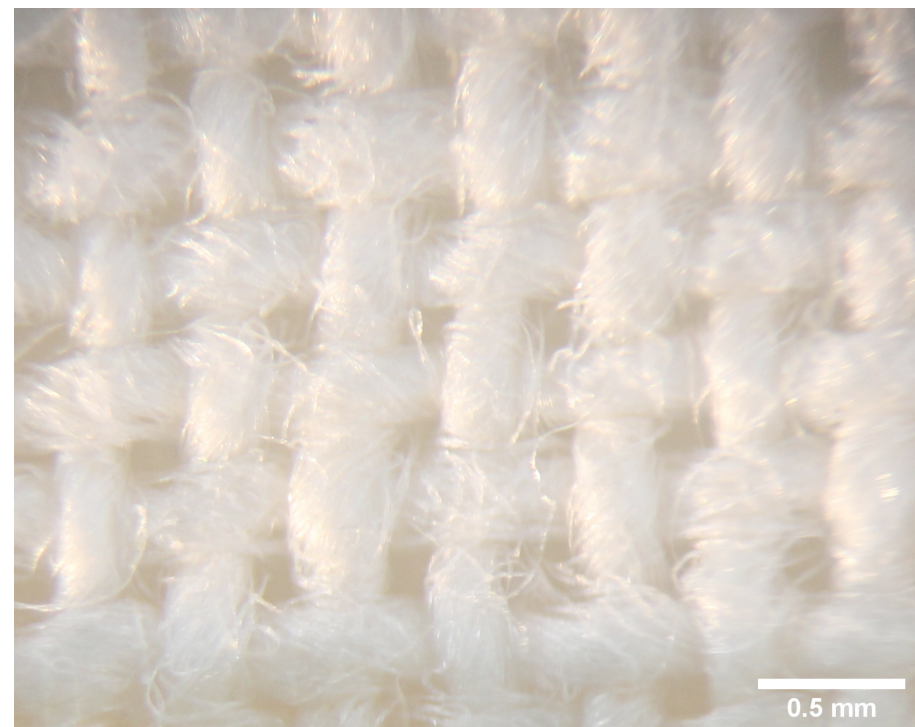


Figure 16. The textiles used in the experimentation: textile A (top) & textile B (bottom)

4.1

Experimentation method – 3D printing onto textiles

While there is plenty of information available about adhesion in the context of 3DP onto textiles, material separation are hardly researched. However, it is equally important for circular fashion. To achieve circularity, the combined materials need to be suitable for separation at the end of their life, so that circulation can be enabled

through recycling of the materials. In this chapter, the second sub-question: “Which parameters favour separation of polymer and textile that leads to re-use or recycling of the original materials?” is answered through an experimental process. The method is divided into three parts: materials, printing process and testing.

4.1.1 Materials

Two polymer types are considered for the experimental testing: PLA and Nylon. While Nylon has shown good adhesion properties, PLA is considered better fitted for 3DP with textiles (Loh et al., 2021; Pei et al., 2015; Rivera et al., 2017). PLA has good adhesion properties, is biodegradable, cost effective and easy to print. On the contrary, it should be noted that PLA has lower printing temperatures than Nylon (200oC - 210oC and 230oC - 260oC accordingly) because of its low melting temperature, which can be a disadvantage. Despite that, PLA is selected as the polymer. The thermal properties of PLA are already listed in table 1 of chapter 3.2.2.

During this experimentation two textile substrates are investigated. The baseline for the textile selection are the following criteria:

- Natural textiles**
The use of natural fibres is preferred against manmade fibres, as they are based on renewable resources and have good recycling options (Harmsen & Bos, 2020).
- Mono-material textiles**
Based on the poor circular potential of blended textiles (Harmsen & Bos, 2020), in the context of this graduation project any kind of blended textile will be avoided and mono-materials are preferred.

iii. **Undyed textiles**
Textile dyes created from petrochemicals can cause environmental degradation and various diseases in living organisms (Lellis et al., 2019), because of their origin and their uncontrolled disposal in the ecosystem. For this reason, it is decided to use and design with undyed or naturally dyed textiles.

Woven cotton fabrics are selected, because they are compatible (good wetting) with multiple types of polymers, including PLA (Pei et al., 2015). Consequently, it is a textile with good properties for experimentation. The literature research showed that textile roughness and thus pore size is one of the most important textile parameters. This parameter is not yet studied in the context of separation, even though a lot of researchers believe that it is a crucial factor for adhesion (Grimmelsmann et al., 2018; Rivera et al., 2017; Sabantina et al., 2015). Therefore, the selected textile substrates originate from the same fibre (cotton) and the same fabrication method (plain weave) with a difference in the pore size. In figure 16 images of the selected textiles are shown and in table 2, some useful properties of the textiles are listed. The microscope measurements are done by taking pictures of the textiles alongside a precise ruler, importing these images in the software called ImageJ and extracting the pictures shown in the table.

Table 2: The properties of the selected textiles. Textile A is a dense woven cotton and textile B is a sparse woven cotton. In the test, textile A is used for prototypes A and textile B is used for prototypes B, accordingly. The values presented are the average and the standard deviation from 10 measurements.

Textile	Textile A – dense cotton	Textile B – sparse cotton	Information acquired from:
Fibre	Cotton	Cotton	Retailer
Fabrication method	Plain weave	Plain weave	Retailer
Yarn thickness	0,27 ± 0,03 mm	0,20 ± 0,02 mm	Microscope
Textile thickness	0,25 ± 0,02 mm	0,21 ± 0,03 mm	Digital Caliper
Pore size	0,17 ± 0,03 mm	0,52 ± 0,08 mm	Microscope

4.1.2 Printing process

The process of creating the polymer-textile interface is 3D printing within textiles. As discussed earlier, this method – which is otherwise called the “sandwich” method, involves the deposition of polymer layers both before and after the placement of the textile on the printing bed. Figure 12 in chapter 3.2 already gives an overview of the printing process. This method is selected because placing polymer layers at both sides of the textile make separation more challenging than printing only on one side of the textile. A successful separation when the polymer is in contact at both sides can be applied easier to specimens with polymer contact at one side, than the other way around.

The process begins with the selection of the 3DP structures. They are selected to be suitable for the evaluation test (which is discussed in the next section) and designed in Solidworks. Then, the model is inserted in the slicer software Cura 4.9., which after the definition of the printing settings (table 3) generates the operational code for the 3D printer. The temperatures are at the upper limit

of the suggested values by the manufacturer. Increased temperatures are selected because they decrease viscosity which improves the penetration of the polymer into the textile pores. The speed is lower than the pre-sets in Cura, because decreased speed offers time to the polymer to penetrate the pores, resulting to enhanced mechanical anchoring too. An important part of the code for printing into textiles is the post processing extension, pause at height. This gives the opportunity to interfere and insert the textile layer after the first 3 layers are deposited.

Following, the code is uploaded on an Ultimaker 5 and the printing process is initiated. PLA is extruded from the printer creating the testing samples until the pause, when the printing bed returns to the starting position and the textile is placed on top of the already printed polymer layers and secured on the platform with 4 clips, 2 on each side (figure 17). After that, the printing is continued (figure 18) until the 3D models are fully printed.

Table 3: The printing settings

Setting Category	Setting	Value
Quality	Layer Height	0.1 mm
	Initial Layer Height	0.2 mm
Infill	Infill Density	100%
	Infill Pattern	Triangles
Material (Temperatures)	Printing Temperature	210oC
	Printing Temperature Initial Layer	190oC
	Platform Temperature	60 oC
Speed	Printing Speed	60.0 mm/s
	Initial layer speed	7.0 mm/s
Post processing scripts	Pause at height (layer number)	3

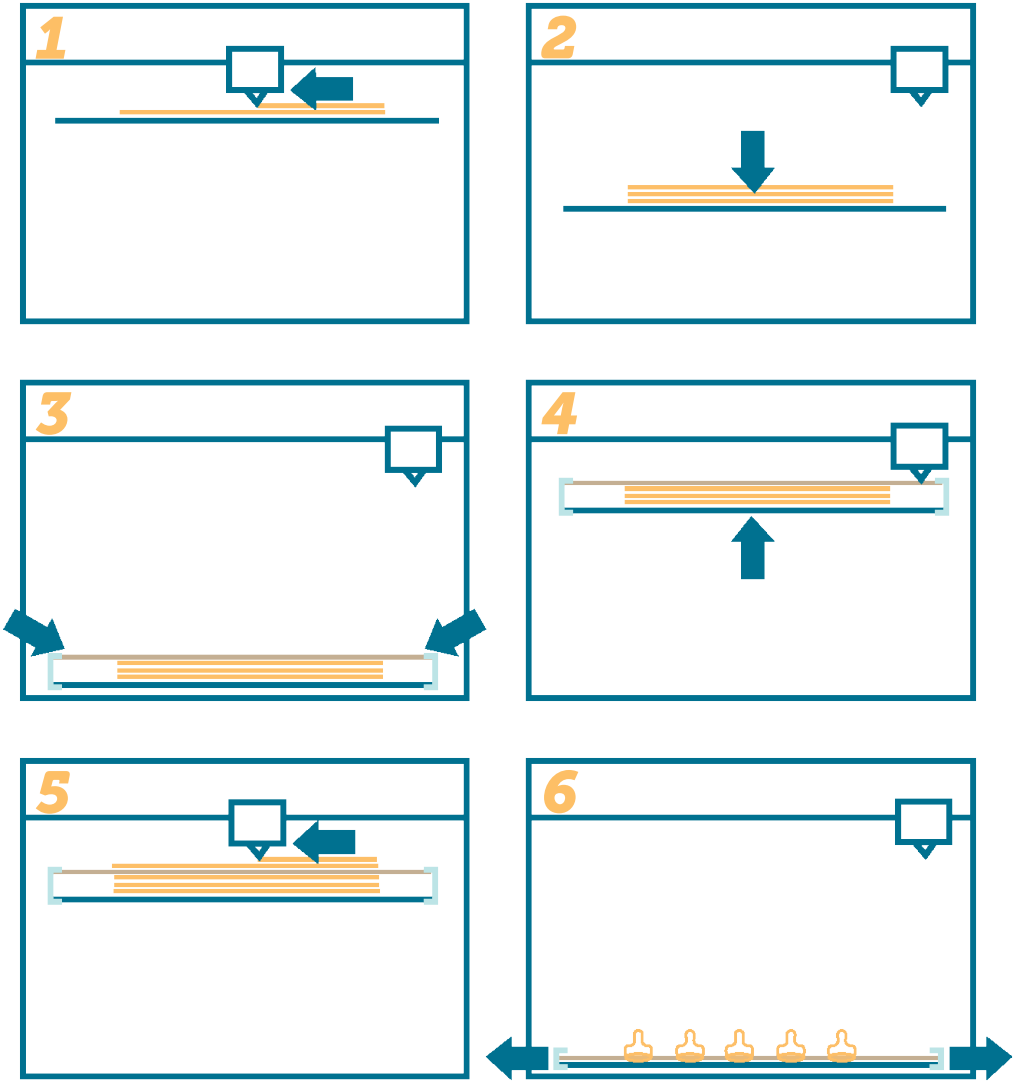


Figure 17. The process of including the textile substrate layer into the print.

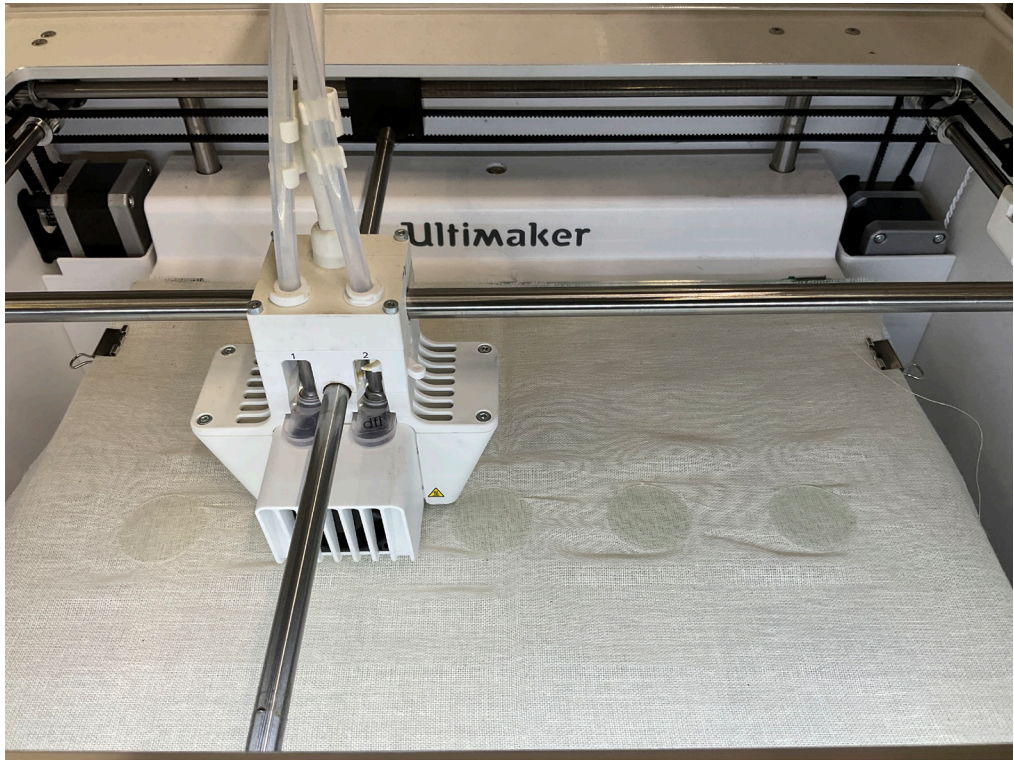


Figure 18. Footage of the printing process after the textile is placed and secured on the printing bed.

4.1.3 Evaluation – Tensile testing method

The evaluation method is perpendicular separation carried out at varying temperature. Perpendicular tensile testing is the most appropriate method to estimate overall adhesion for 3DP onto textiles (Malengier, Hertleer, Cardon, & Langenhove, 2018); thus, it is deemed appropriate for the test. Performing a vertical tensile test will provide insight into what is the force that each prototype can withstand before critical failure and what is the elongation before critical failure. The possible critical failure types are: adhesive failure, cohesive failure and substrate failure, which is also a type of cohesive and is attributed to the substrate’s properties and fabrication (figure 19). The experiment is repeated once in room temperature (21oC) and once with increased local temperature (40oC).

However, this does not constitute a common tensile test. For this reason, based on previous research (Malengier et al., 2018; Gorlachova & Mahltig, 2021) a dolly (figure 20) is printed onto the textile and then it is clamped at the upper side of the tensile machine, while the ends of the textile are extended around the bottom layers of the 3D printed structure and clammed at the bottom side (figure 21). The adhesion is tested by using force measurements during separation with a machine Zwick/Roell Z010 and the software used is testXpert II. The testing set-up for this experiment is described in detail in table 4 and shown

in figure 22. The specimen used for this test does not exist in the inventory and the closest one to that is a flat specimen, which is the one selected. Nonetheless, there is a difference in thickness between the upper side with the dolly and the bottom side with the textile. To perform the test correctly, the two grips when closed should be aligned, therefore the bottom grip is displaced 4mm.

The measured values of the test are:

- A. the peak force detection in Newton, which indicates the force needed for separation
- B. the force at initial failure in Newton, which indicates interface longevity

Generally, temperature is an important factor in generating the interface through 3DP. Thus, it is considered as potential factor for improving separation and circularity of the interface at the end of the use. Hot air it is selected because it can potentially be upscaled to larger quantities of products.

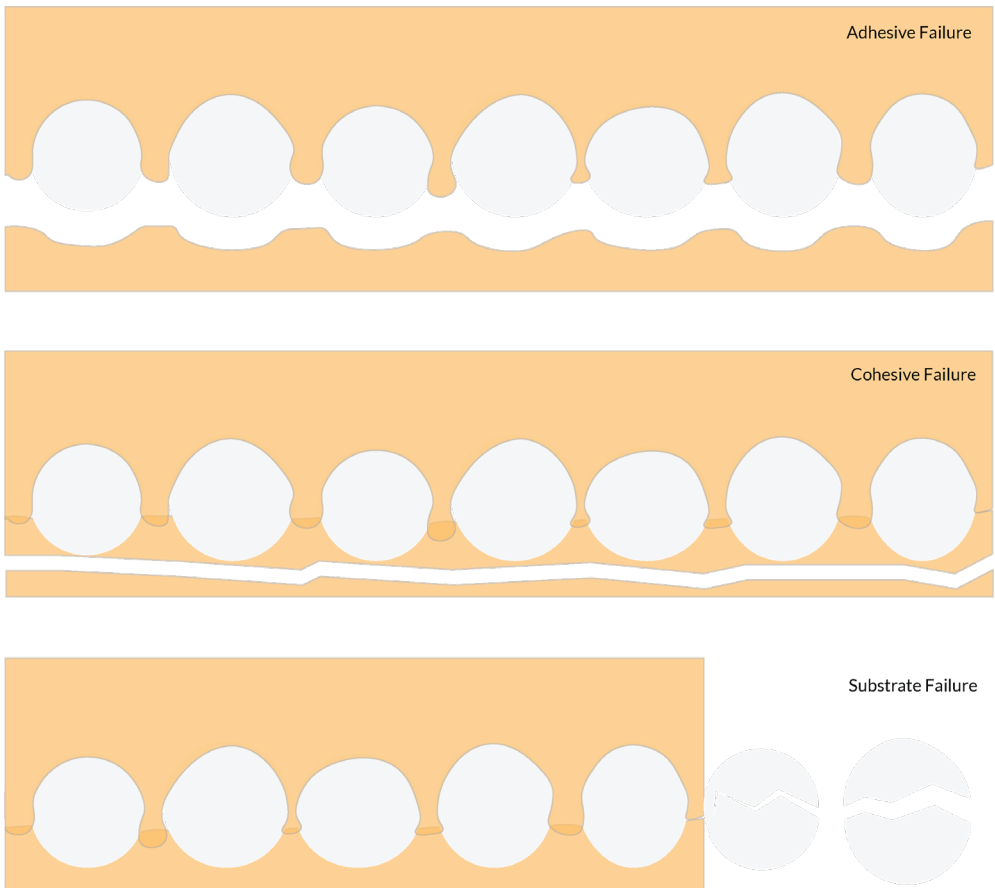


Figure 19. Different types of possible critical failures (inspired from “Biolin Scientific”).



Figure 20: The dolly used, size: 23.8 x 24 mm (Malengier et al., 2018; Gorlachova & Mahltig, 2021). Top side (left) and bottom side (right).

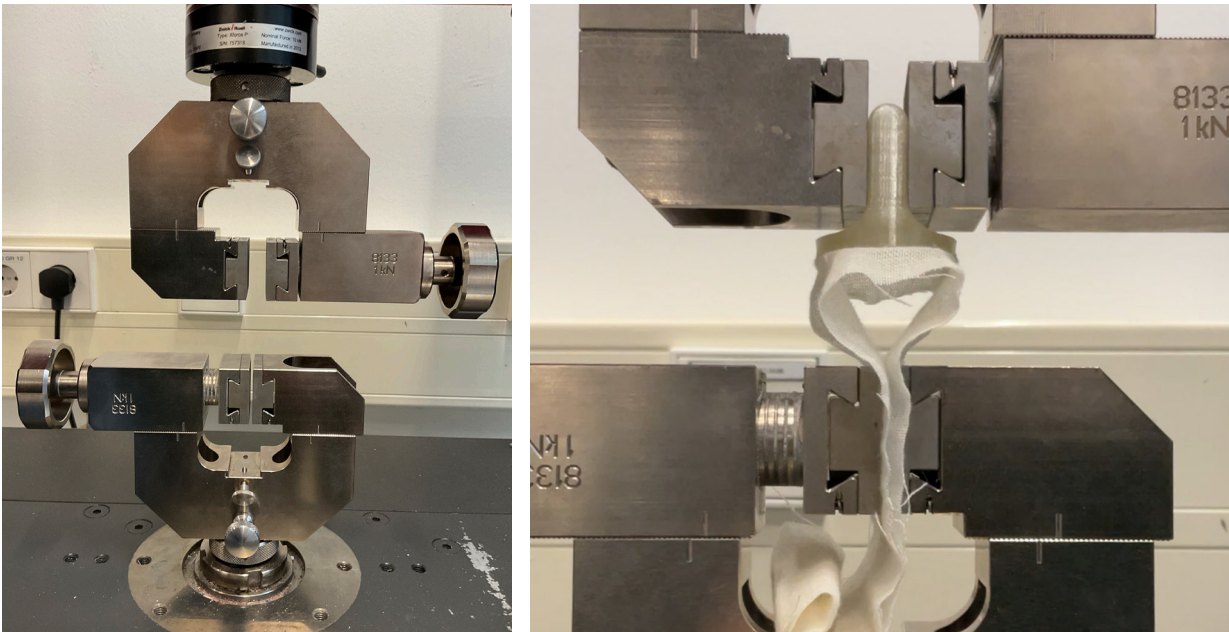


Figure 21: Perpendicular tensile testing for polymer-textile interfaces. Current testing setup and without the sample (left) and with the sample (right).

Table 4: Perpendicular Tensile Test Specifics

Parameter	Value
Load cell	10 kN
Grips Crosshead	0.5 kN
Specimen	Flat
Distance between top clamp and adhesion surface	9 mm
Distance between clamps	32.48 mm
Test speed	50 mm/min
Force Shutdown Threshold	20%

4.2 Results and discussion

The glass transition temperature of PLA is mentioned in table 1 and can vary depending on the amount of residual monomer. Dry cotton is estimated to have a glass transition temperature of 220°C, with the value dropping to below zero when saturated with water (Huson et al., 2017). Since PLA is expected to deform first, the selected temperature for separation is based on its properties. Thus, to compare the impact of heat, two temperatures

would be tested, room temperature (21oC) and 40oC. This temperature is selected so that the PLA is softened, but does not start to melt. A Steinel heat gun is used to increase the temperature and an RS 1319A K-Type Thermometer is used to measure the local temperature around the sample. The textiles used in this test are textile A, for prototype A and textile B for prototype B. Reproducibility was established by the repetition of each test 5 times.

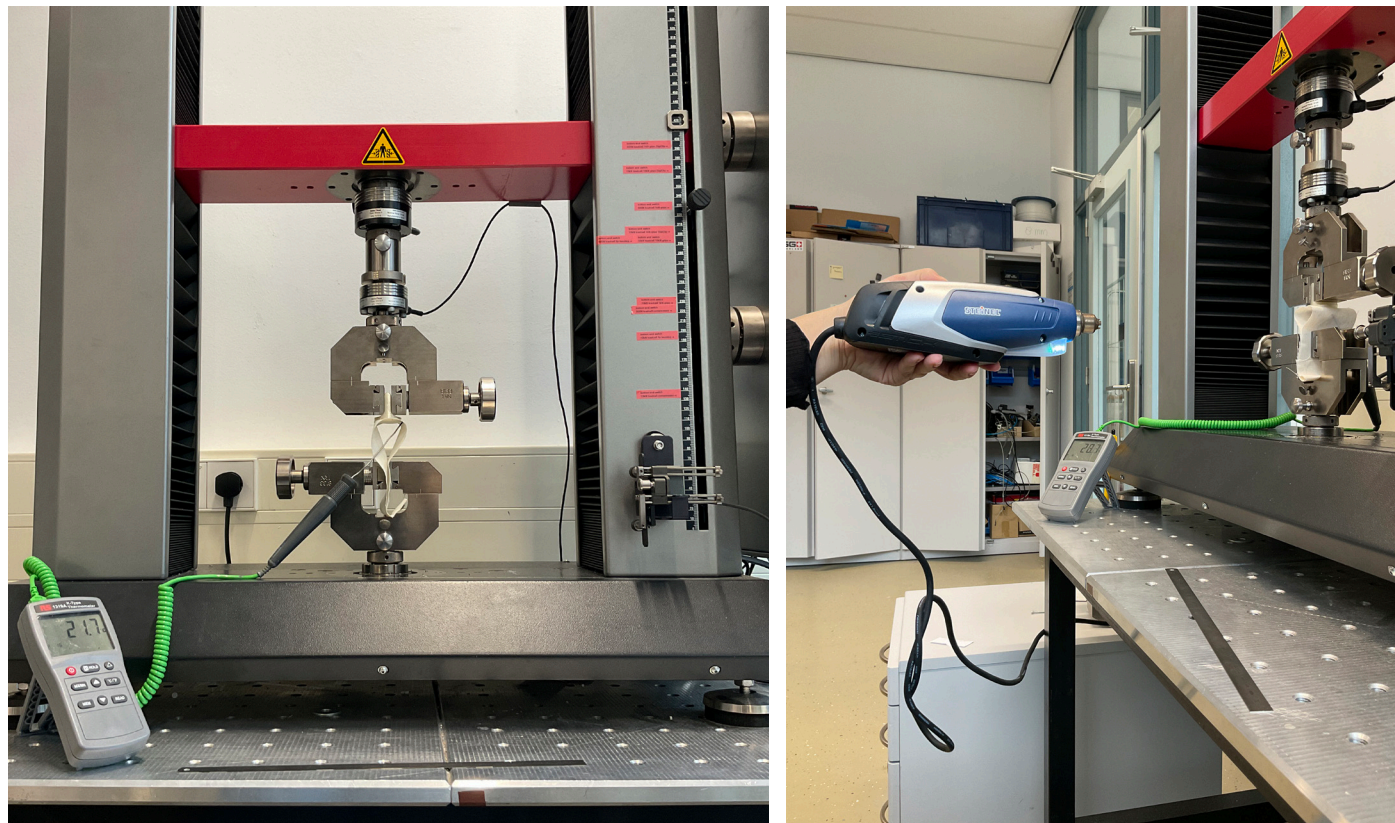


Figure 22: Test set-up with heat gun and thermocouple.

The samples produced are shown in figure 23. After the test is realised, the samples are separated and have reached a type of critical failure (figure 19). The results are observations regarding the failure type that occurred and the forces needed to reach critical failure and separation.

Observations

(i) Tensile test at 21oC: The critical failure at prototype A samples is more evident, since the polymer is clearly separated, fully on the bottom and partially on the top (one-sided adhesive failure). Regarding the textile, after the test it remains intact. On the contrary, the critical failure of the prototype B samples is located at the textile (substrate failure), which gets deformed and destroyed, while the polymer stays intact in this case.

(ii) Tensile test at 40oC: Textile A and PLA model are now fully separated, with only few free-standing fibres still attached on PLA because of two-sided adhesive failure. Textile B does not have a visible difference from the experiments in room temperature and still reaches substrate failure. The different behaviour between the two textiles is determined by the extent of mechanical interlocking and is possibly attributed to the encapsulation of fibres. To better observe the materials after separation, microscopic images are taken. Figures 24 show the two materials and figures

25 show the two parts of the dolly after full separation.

Additionally, it is evident that the separation in the context of interfaces is best described by the term delamination. Delamination is a separation along a plane parallel to a surface (Nijland & Larbi, 2010), as in the separation of the polymer 3D printed layers from a textile substrate.

Analysis

Table 5 shows the average and standard deviation values for the force at initial failure and the peak force, and the type of critical failure for prototypes A and B for both perpendicular tensile tests (at 21 and 40oC). First column of the table indicates the prototype, column 2 the property and columns 3 and 4 display the values of the properties for the test in room temperature and in 40oC respectively. Forces are measured in Newton. The results of the force at initial failure are illustrated in figure 26. The results of the tests in detail are included in appendix D.

When performing the experiment, there are numerous factors that influence its accuracy. It is nearly impossible to control them 100% and when the experiment is repeated receive the exact same results. Such factors can be random errors or uncontrollable conditions and are recorded in table 6.

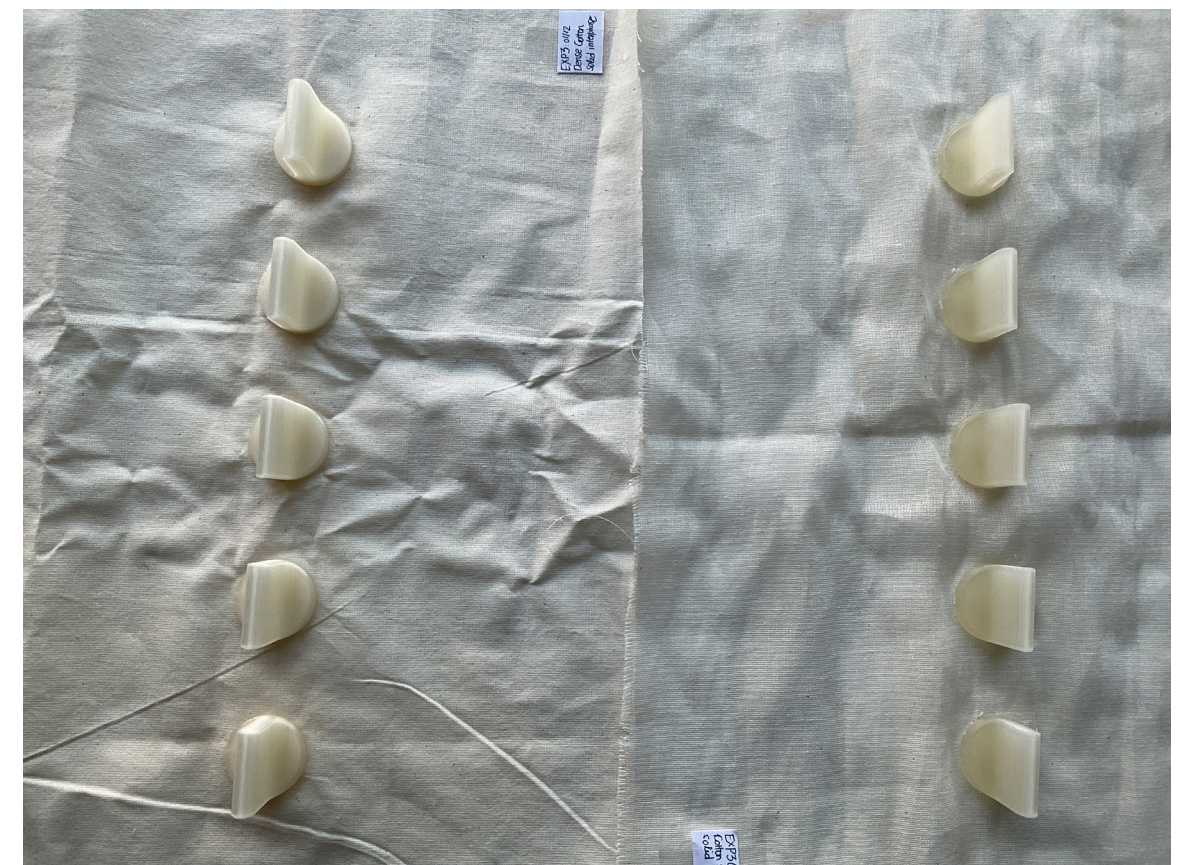


Figure 23: Dollies before the test. Left - small pore size (textile A), right - large pore size (textile B).

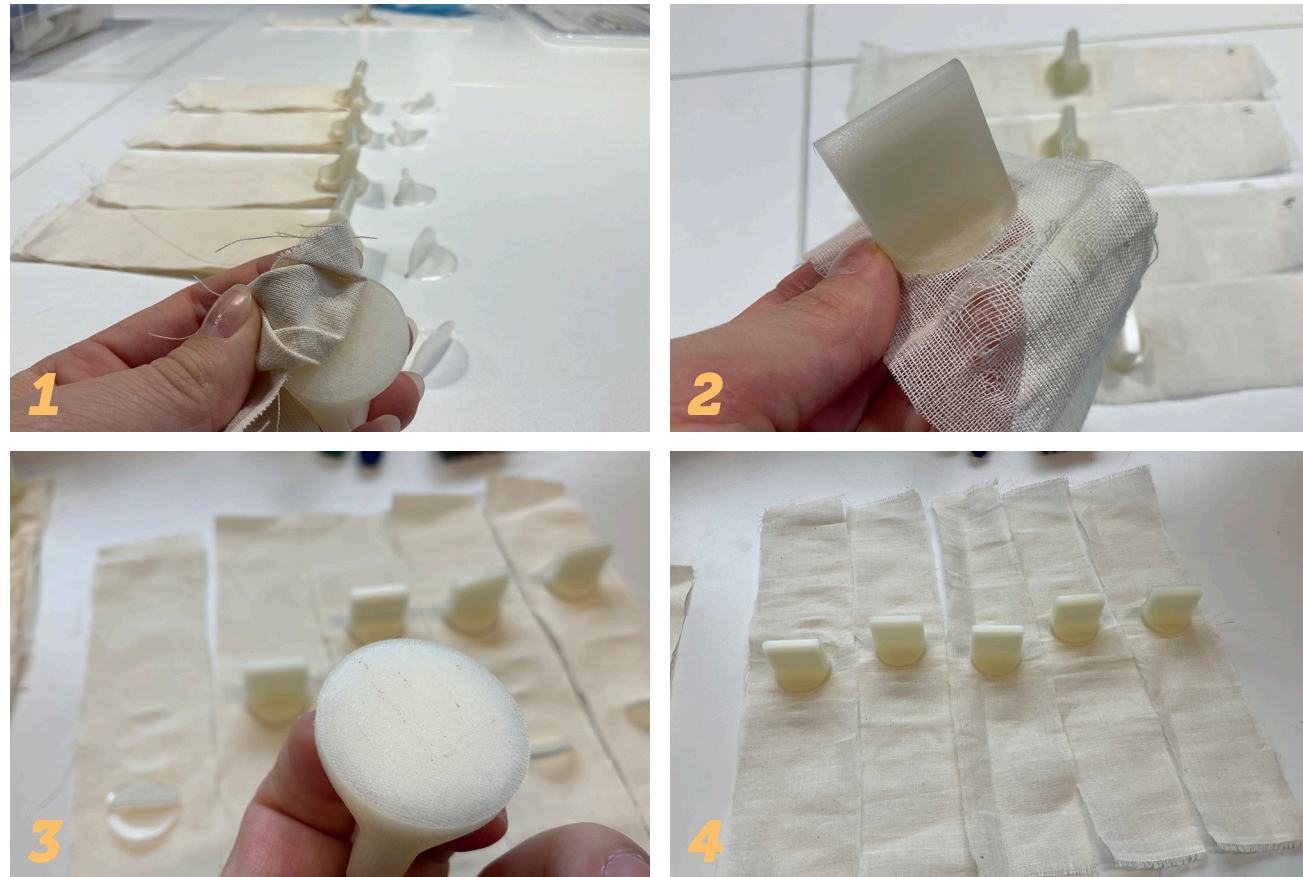


Figure 24. After the test at 21oC – textile A reaches one-sided adhesive failure (1) and textile B reaches cohesive failure on the textile substrate (2). After the test at 40 oC– textile A reaches two-sided adhesive failure (3) and textile B reaches again failure on the textile substrate (4).

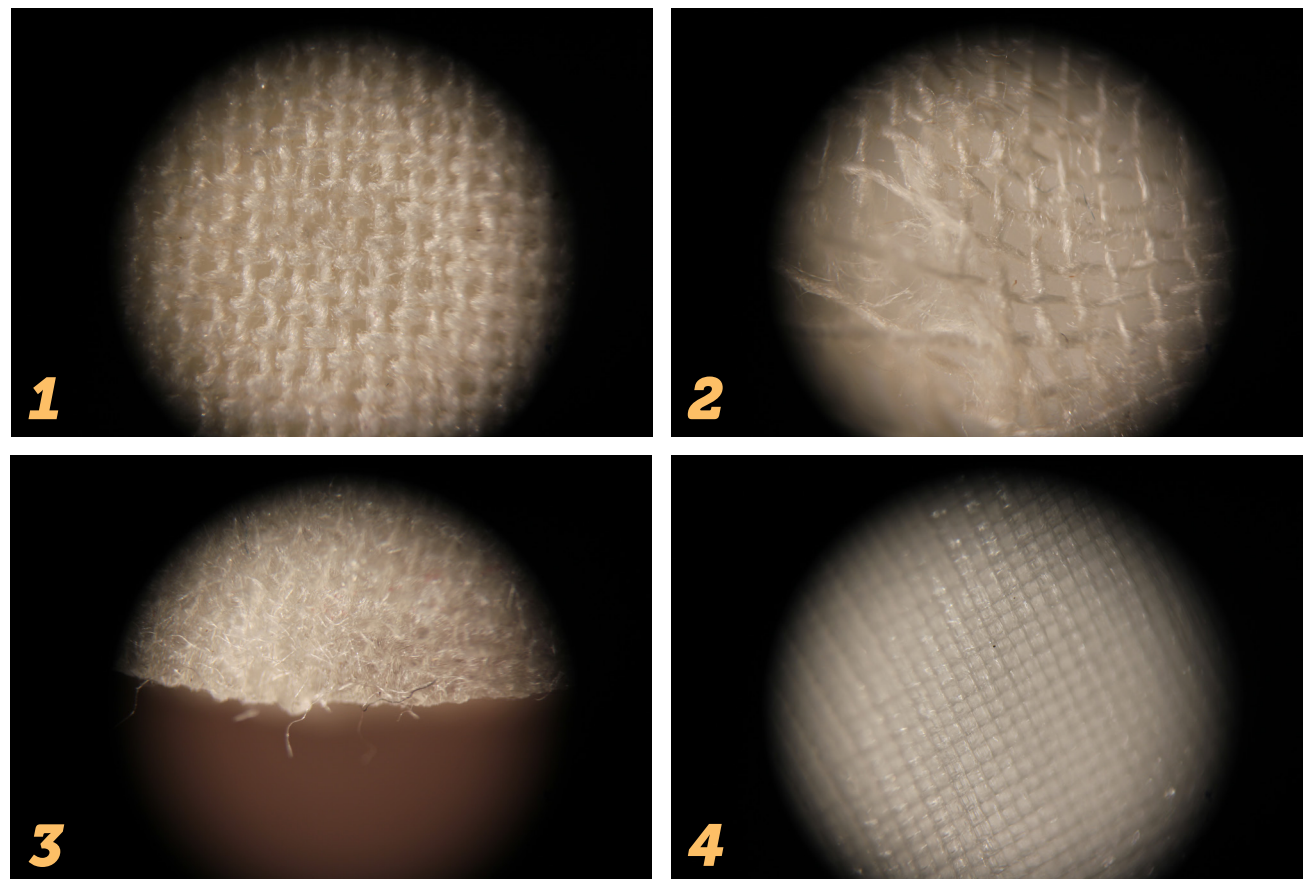


Figure 25. Microscopic images after the test at 40 oC– textile A (1) and textile B (2), upper layers with free standing fibres (3) and bottom layers (4).

Table 5. The force at initial failure, the failure type and the peak force for prototypes using textile A and B at perpendicular tensile tests performed in local temperature of 21 and 40oC.

		Perpendicular Tensile test at 21oC	Perpendicular Tensile test at 40oC
Prototype A - Textile A	Force at initial failure	37,6 ± 11 N	28,3 ± 6,4 N
	Failure type	One-sided adhesive	Two-sided adhesive
	Peak force	97,3 ± 20 N	93,3 ± 11,1 N
Prototype B - Textile B	Force at initial failure	30,5 ± 12,2 N	34,3 ± 15,9 N
	Failure type	Cohesive (Substrate)	Cohesive (Substrate)
	Peak force	80,9 ± 21,8 N	57,1 ± 3 N

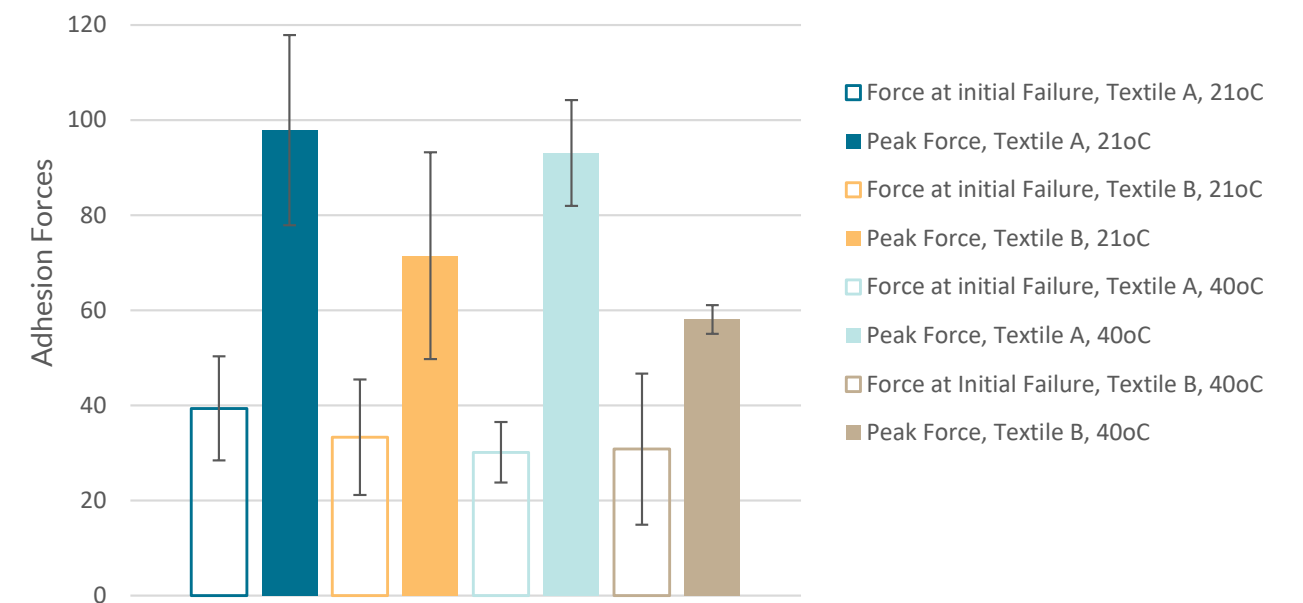


Figure 26. Comparison of adhesion of 3D printed structures printed onto two different cotton fabrics for two different temperatures. Adhesion represents the force at initial failure or the peak force, and the bars illustrate the performance of the prototype categories.

Table 6: Possible errors during the test.

Materials	1/ Invisible imperfections on the textile.
	2/ Differences in textile surface free energy, yarn roughness and free-standing fibres affect the results more than the pore size.
	3/ Production of the filament could create invisible imperfections.
Printing Process	4/ Change of the conditions in the printing chamber during printing (if someone opens the window and cold air flows in that suddenly reduces the temperature)
	5/ Accidental stop of the printing process might cause a model with different characteristics.
	6/ Some leftover material in the printer could be later on printed on the samples.
Test Process	7/ The textile or dolly might not be clapped at the exact same location during the test.
	8/ The specimen type is not standard; therefore, the calculated values might deviate.
	9/ The first test might need adjustments and could lead to not accurate results.
	10/ Larger distance between the two grips would create a higher moment of inertia and therefore higher separation forces, as would a shorter distance accordingly.
	11/ The room might be warmer or colder because of the temperature released by working machinery.

4.3

Conclusions

Insight 1:
Increased textile roughness leads to irreversible polymer-textile bonds.

Adhesive failure is preferred to substrate failure, because it results into material separation. In this experimentation it is found that textile B reaches substrate failure before separation, which prevents the polymer-textile interface from being recycled. Substrate failure not only keeps the two materials together, therefore defeating the purpose of perpendicular force as a separation mechanism, but also damages the material quality of the substrate, which undermines the product circularity. Nevertheless, the force averages recorded at initial failure for the two textiles confirm the literature research, which concludes that textiles with increased roughness form more resistant polymer-textile bonds than textiles with decreased roughness. The lower average of peak forces of prototype B, is attributed to the textile construction and not the polymer-textile bond.

Insight 2:
Increased local temperatures during separation enables polymer-textile bond reversibility.

The separation between polymer and textile A is improved from one-sided to two-sided adhesive failure, by local temperature increase from 21 to 40oC. This is supported by the peak force data in table 5, which prove that separation at increased local temperatures requires lower forces for separation. Also, as discussed in earlier chapters, the increase of fabric recycling (reuse of textile) rates depends on the quality of the retrieved materials and the material separation rates (Roos et al., 2019; Sandin & Peters, 2018). Hence, to enable Loop 1 (figure 5), performing the separation at 40oC is preferred than at 21oC. In this case, the textile goes back to the part level (textile) and the polymer is recycled back to the material level (Bioplastic PLA).

In the beginning of this chapter, it is established that the difference between textiles A and B is the pore size. Gorlachova & Mahltig (2021) suggest that the mechanical stability of a textile can be the defining factor for a separation that results into intact or damaged materials. This leads to the conclusion that there is a relationship between pore size and mechanical stability of textiles. Nonetheless, amongst textiles A and B, textile A is better suited for material separation, because separation of prototypes that embody textile A result into high quality recovered materials. The textile selection completes the second key principle of design for disassembly – material selection.

From the experimental testing it can be concluded that the parameters that influence polymer-textile interface separation leading to recycling are local temperatures during the separation process and textile properties such as pore size. The results showed that increasing the room temperature of 21oC to 40oC improved clean separation and the textile substrate with the smaller sized pores (textile A) has more potential to be recycled in comparison with the textile substrate that has larger sized pores (textile B). While these insights help answering the second sub-question, the next step is to choose a product application that can embody the research and take it a step further.

5.

Design possibilities and selection of the footwear mid-sole

5.1

The design spectrum

– what product types could benefit from this research

3DP onto textiles has a wide range of application purposes. Multi-material 3DP allows the creation of heterogeneous textile composites with different local properties. The polymer can be used to create functional, decorative or protective elements on a textile. The aspect that matters the most for the applications discussed in the context of this project is the connection and contribution to circular fashion. This part of the chapter depicts an exploration of the solution space where circular textiles and 3DP into textiles intersect. This space is here named: “design spectrum” and a representation of it is figure 27.

The design spectrum constitutes from applications that either already use 3DP within textiles, or applications that could benefit from applying this method. The horizontal axis represents the market, from industrial applications, to more artistic forms of expression. The vertical axis represents the size, from micro to macro level.

The applications are grouped in the following general categories: objects/furniture, wearables, spaces, footwear, details and haute couture. It is evident that they are not only limited in fashion; architecture and interior design are sectors where textiles have a variety of applications and potential and it is important to include product types from all three of these categories. Wearables, footwear and haute couture are connected to fashion, spaces to architecture and finally objects to interior design. The details cluster can be allocated to all three categories.

The method of 3DP onto textiles could benefit each product application in a different way. It can facilitate

product disassembly at the EoL through creative interface design, form adaptation, form freedom or textile effects. Each of these advantages can add value on the product. The values are sustainability, functionality, innovation and aesthetics, accordingly. A legend showcases what added value each product benefits from.

(i) Circularity – The usage of 3DP in complicated products can improve their EoL potential through design for disassembly by minimizing the number of materials used in a single product along with unsustainable connection methods, such as gluing and or stitching. These methods are not desired, because removing them can compromise the material quality at separation. 3DP onto textiles can be reversed and allow for disassembly at the EoL.

(ii) Functionality-Form adaptation refers to making use of the material properties and applying 3DP onto textile in a way that it can create new forms and add new functions to the textile.

(iii) Innovation - Using 3DP in combination with textile can increase the possibilities of creation and reduce the constraints of construction, providing designers with form freedom and possibilities for innovation.

(iv) Aesthetics – In haute couture, mostly, designers use the method to enrich the aesthetics of their creations, sometimes through employing the method to produce a textile effect. This method brings the materials together by using the textile as a connector, keeping together the structures of the 3D printed material, which works as the textile – to create pieces of impressive aesthetic.



Figure 27. The design spectrum: the possible product applications for implementing 3DP onto textiles and the added value of the method (disassembly at EoL, form adaptation, form freedom and aesthetics).

5.2
Selection process
- what makes a footwear the circular challenge

The design spectrum shows the design opportunities for 3DP within textiles. In the interest of making an informed decision about the application criteria are developed. Whereas all the values mentioned previously are important, sustainability is the most relevant to the topic of circular fashion. Therefore, the criteria are based on different aspects of circularity and EoL. Apart from the criteria, there are some boundary conditions that the application should comply to. A practical issue like size should be considered together with complexity, which should be in accordance with the workload of a graduation. Table 7 lists the criteria, listed in descending order of importance, and the boundary conditions that contribute to the application decision.

The product categories are evaluated through the application of the Harris Profile method, where the product categories score between -2 and +2 based on their satisfaction of each criterion (figure 28). For criterion 1, the most impact on disassembly would be for footwear, because it is a product with multiple components that are securely bonded together, in a lot of cases without a disassembly plan. Therefore, 3DP onto textiles could simplify the process and improve EoL, in contrast with other product categories such as objects or wearables, where 3DP onto textiles could introduce complexity regarding disassembly at the EoL. As for longevity, products which are subjected to daily wear and affecting environmental conditions without protection receive a lower score (furniture and footwear).

Functionality innovation to replace unsustainable materials mostly contributes to products that constitute of a variety of different materials. Footwear received the highest score because, currently every single item is manufactured by an average of 40 materials (Abu et al., 2017) and thus, there is a lot of possibilities for improvement. For other wearables and couture, it actually introduces more materials and complicates EoL, so they receive the lowest score among the rest of the product categories. Finally, aesthetics can be applied in all categories to enhance attachment with the user and it matters the most for couture, since it is an artistic expression. Regarding the size and complexity boundary conditions, the details receive the highest scores.

The result of the evaluation indicates that footwear is the product category that could benefit the most from 3DP onto textiles. It is worthy to mention that product details scored the best in the boundary conditions, thus a combination of footwear with details is a possibility that can satisfy both circularity criteria and the boundary conditions. Since the design of a complete footwear can be a great challenge and require a team working on it fulltime for months, the focus is narrowed down to aspects that concern the circularity and relate to adhesion and delamination. For this reason, the design is limited to a single part of a sneaker, the mid-sole (figure 29), and its connection to the fabric (rest of the shoe). Next chapter researches how separation can be applied on the selected product.

Table 7. Criteria and boundary conditions that lead to the application selection.

Criteria	1	Disassembly	The use of 3DP onto textiles should contribute to circularity by forming reversible connections that enable design for disassembly and recycling.
	2	Longevity	The adhesion between polymer and textile should be strong enough to withstand the forces applied during the usage phase of the product and the environmental conditions.
	3	Functionality innovation	3DP onto textiles develops products with different local properties and innovative structures that create new possibilities and functions to replace materials that complicate EoL.
	4	Aesthetics / user attachment	3DP onto textiles should add an aesthetic value to the product, so that users want to prolong their lifetime.
Boundary Conditions	5	Size	The design should be able to be printed with an Ultimaker 5.
	6	Complexity	The design complexity should not be overwhelming (computational models etc.).

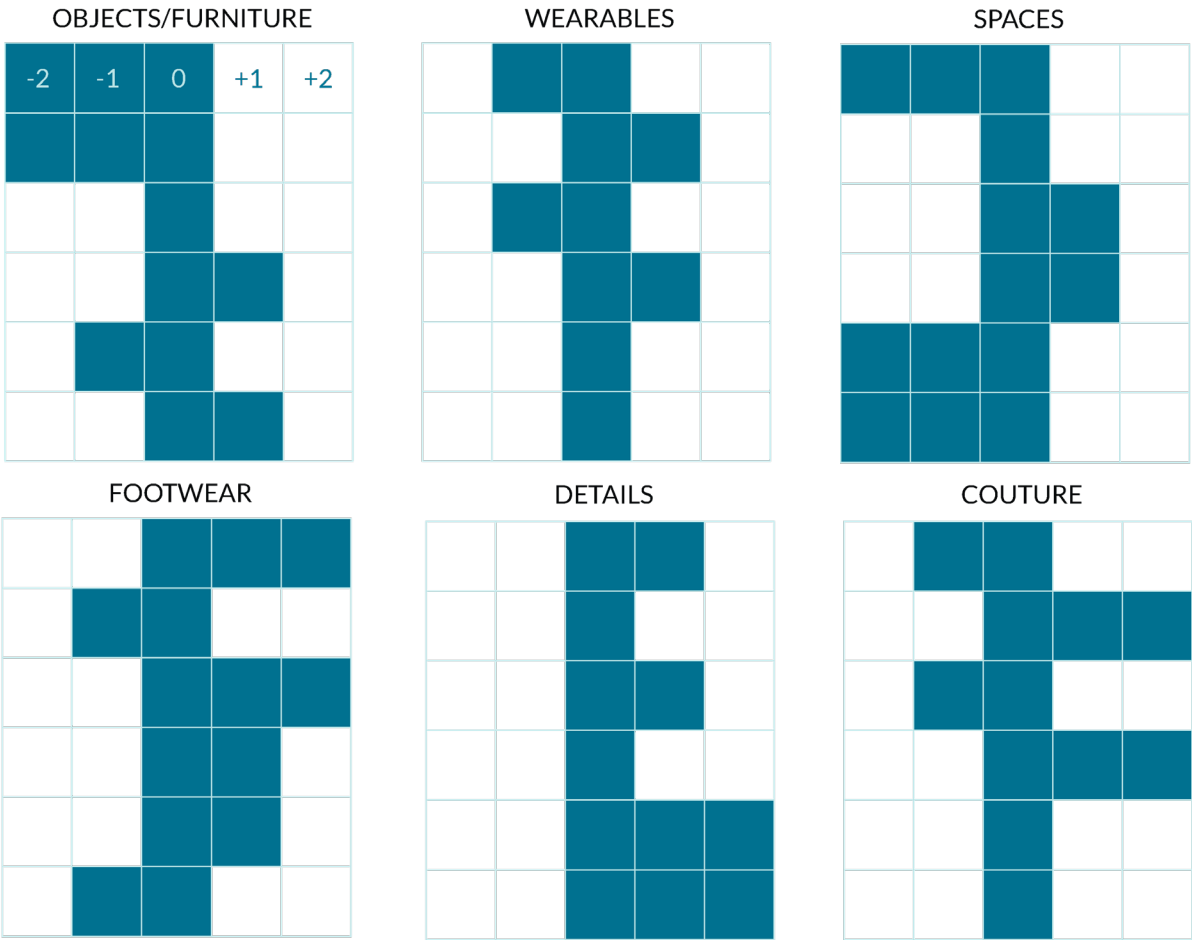


Figure 28. The Harris Profile evaluation. The evaluated property that tends to fall on the right (received the highest scores on the most relevant categories) is the most desirable one. The product category that fits this description is footwear.

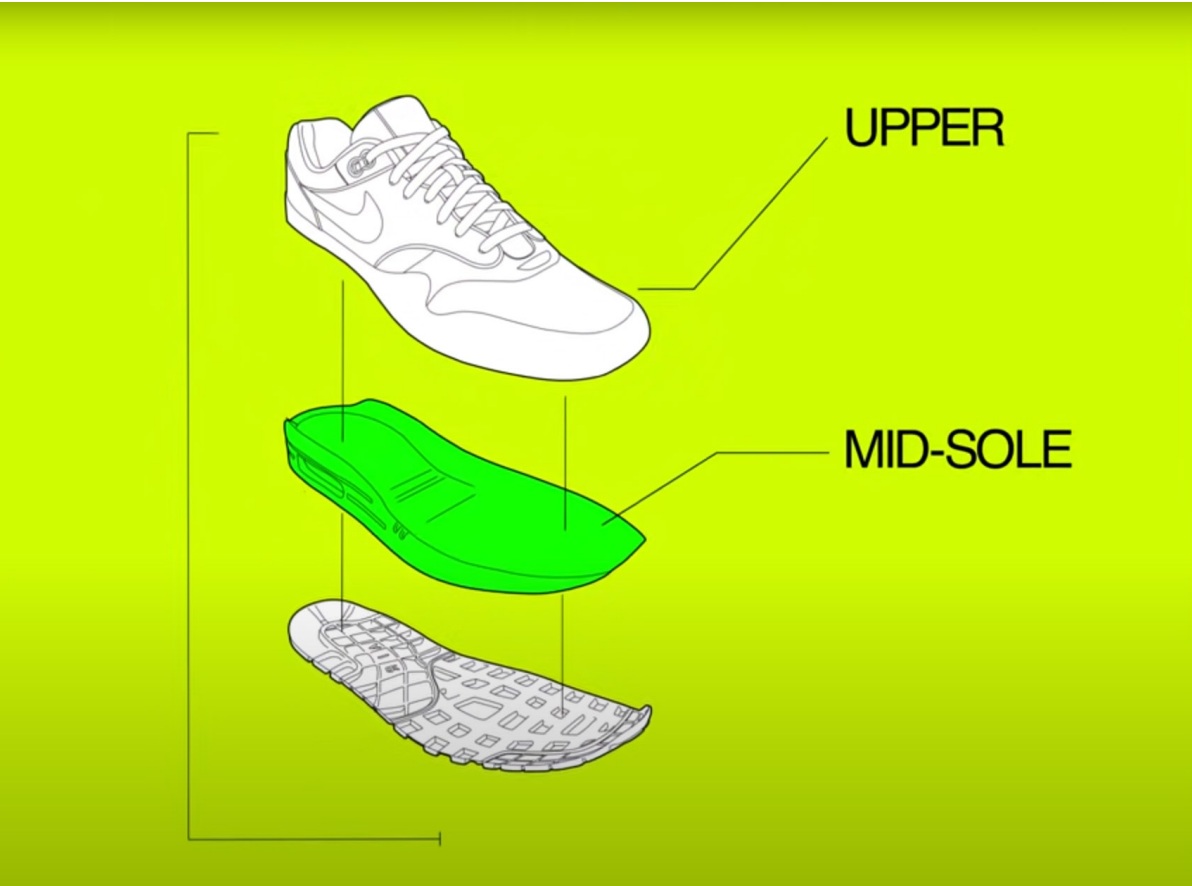
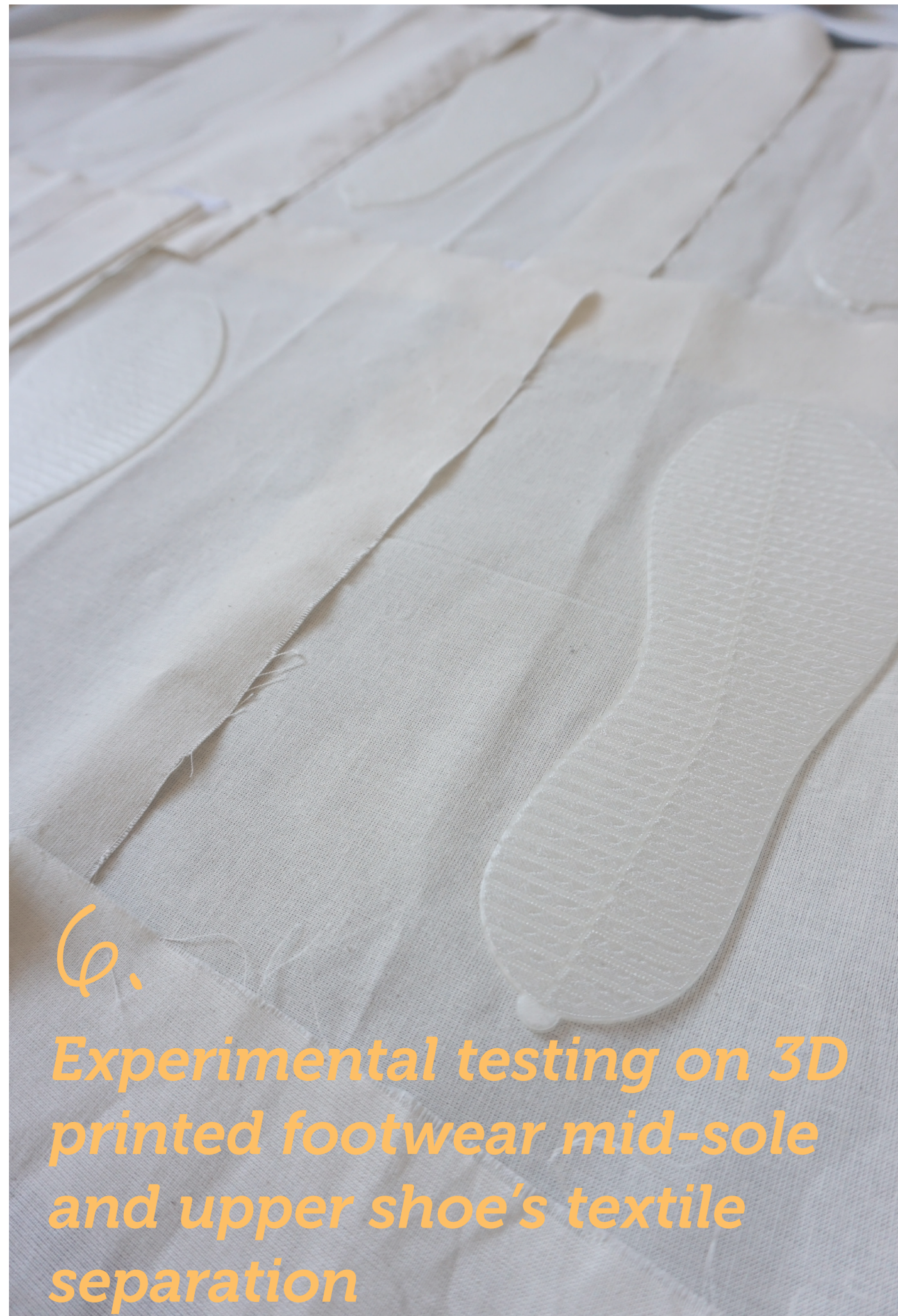


Figure 29. The typical shoe composition by Nike (From Trash to Space Hippie | Behind the Design | Nike https://www.youtube.com/watch?v=i3n_4-c1Rg8).



6.1 Experimental testing background

From the literature research it is evident that contact area influences adhesion and thus separation. In the experimental testing it is found that increased contact area (resulting from increased textile roughness) negatively impacts separation. Hence, an increase in size (from testing dolly to sneaker mid-sole) will consequently increase the adhesion and prevent separation (figure 30).

Fortunately, the polymer-textile contact area also depends on the surface area, except for the size of the 3D printed structures. Through designing the polymer-textile interface, the contact area can be manipulated to allow for material separation. In this chapter, four different design variations are tested in regards to separation forces.

During separation at the EoL of the product, the polymer-textile interface is exposed to perpendicular and shear forces. In product applications, usage conditions need to be considered too, since longevity is equally important to separation. Footwear soles are exposed to repeated loading that can lead to separation before the product's EoL, through deformation during walking. Walking bends the sole in both directions of the z-axis (figure 31).

To summarize, in this chapter two separation tests (one representing separation at EoL and one representing a possible separation scenario during usage) will be performed to evaluate four different footwear mid-sole designs that are printed and hence attached to the textile of the upper shoe.

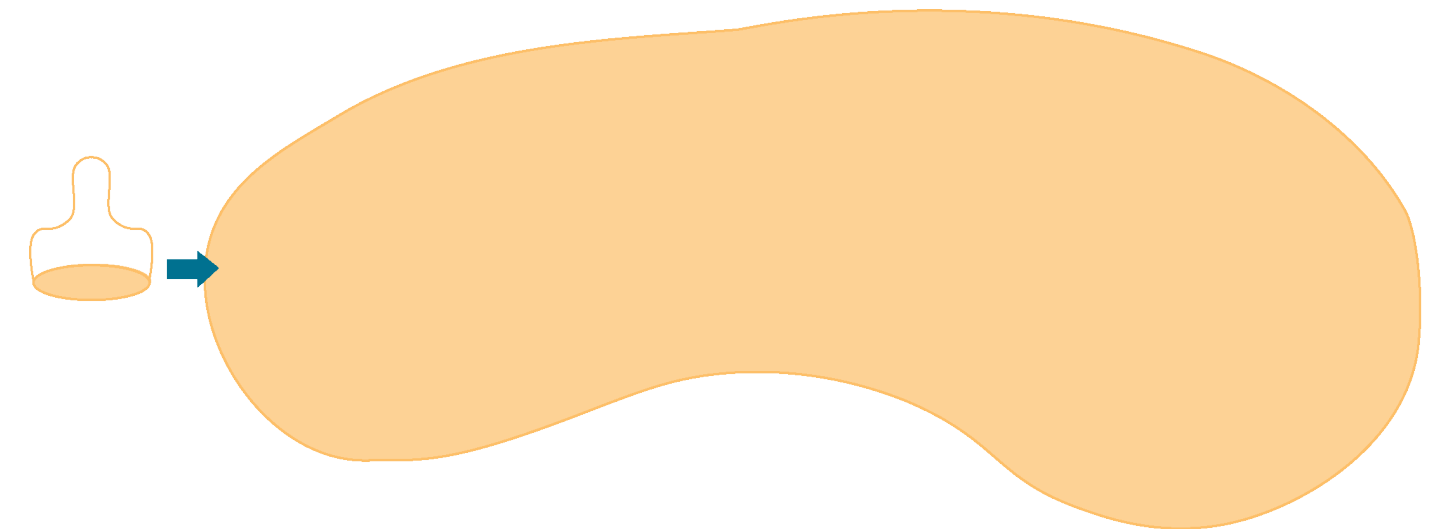


Figure 30. The difference in size and therefore surface area, when transitioning from the experimental dolly to the footwear mid-sole.

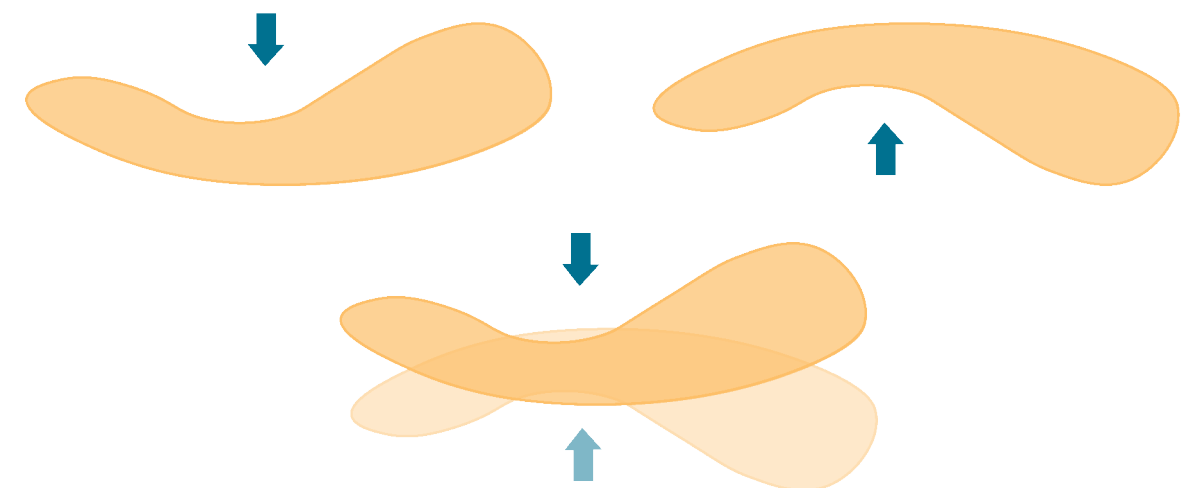


Figure 31. A representation of the mid-sole repeated loading.

6.2

Experimentation method

6.2.1 Sample development

During this experimentation, the materials used are PLA as the polymer and dense woven cotton (table 2 - textile A), as the textile. The printing process is the same with the one explained in chapter 4.1.2. The 3D structure

printed onto the textile is a woman's EU38 size footwear mid-sole. The prototypes consist of four types of layers: top, middle, textile and bottom (figure 32 & table 8).

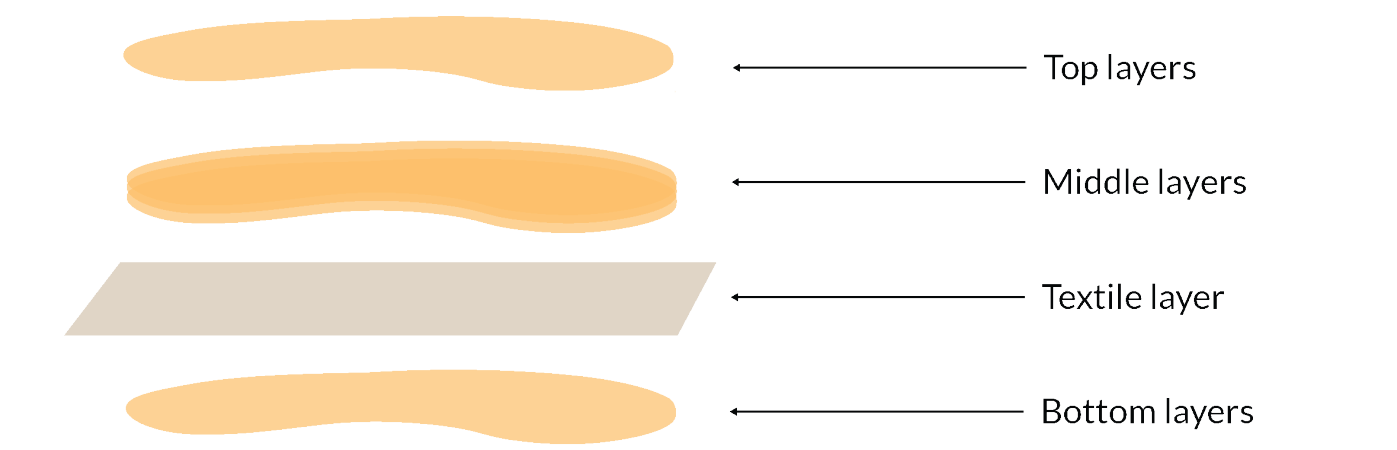


Figure 32. Visual explanation of the four different layer types that constitute each prototype.

Table 8. The characteristics of each layer type: material, number of layers used, layer thickness and infill.

	Name	Material	Number	Thickness	Infill
1	Top	PLA	3	0.3mm	100%
2	Middle	PLA	23	2.3mm	Design variation
3	Textile	Plain woven cotton	1	0.25mm	85%*
4	Bottom	PLA	3	0.4mm	100%

The interface is defined by the middle layers, because they come in contact with the textile. Thus, the design of these layers is key to enabling separation at the EoL. Bottom layers are less likely to adhere (Rivera et al., 2017), therefore it is selected to print them with 100% infill, similarly to the top layers. The textile infill is calculated by the yarn and pore surface areas:

$$\frac{(0.17 + 0.27)^2 - 0.17^2}{(0.17 + 0.27)^2}$$

The four design variations of the middle layers are shown in figure 33. Design 1 is a 100% infill model that serves as a baseline for the experiments. Design 2 is a mesh and it is

selected because it provides a skeleton that can withstand deformation in both directions. Design 3 is meant to be perpendicular to the separation direction, which happens from heel to toe. Finally, design 4 is the same as 3 but includes a backbone in the centre so that the distance between sides is half as much to provide more support. In table 9, the differences in surface area and infill are shown. First of all, in comparison with the 100% infill dolly of the experimental testing on polymer-textile interface separation, the surface area of the 100% infill sneaker mid-sole (design 1) is 32 times larger. Designs 2 and 3 are close to size of their surface area, which is around 22 and 23 % of design 1 and design 4 is 25 % the size of design 1. The prototypes produced through this process and used for the testing are shown in figure 34.

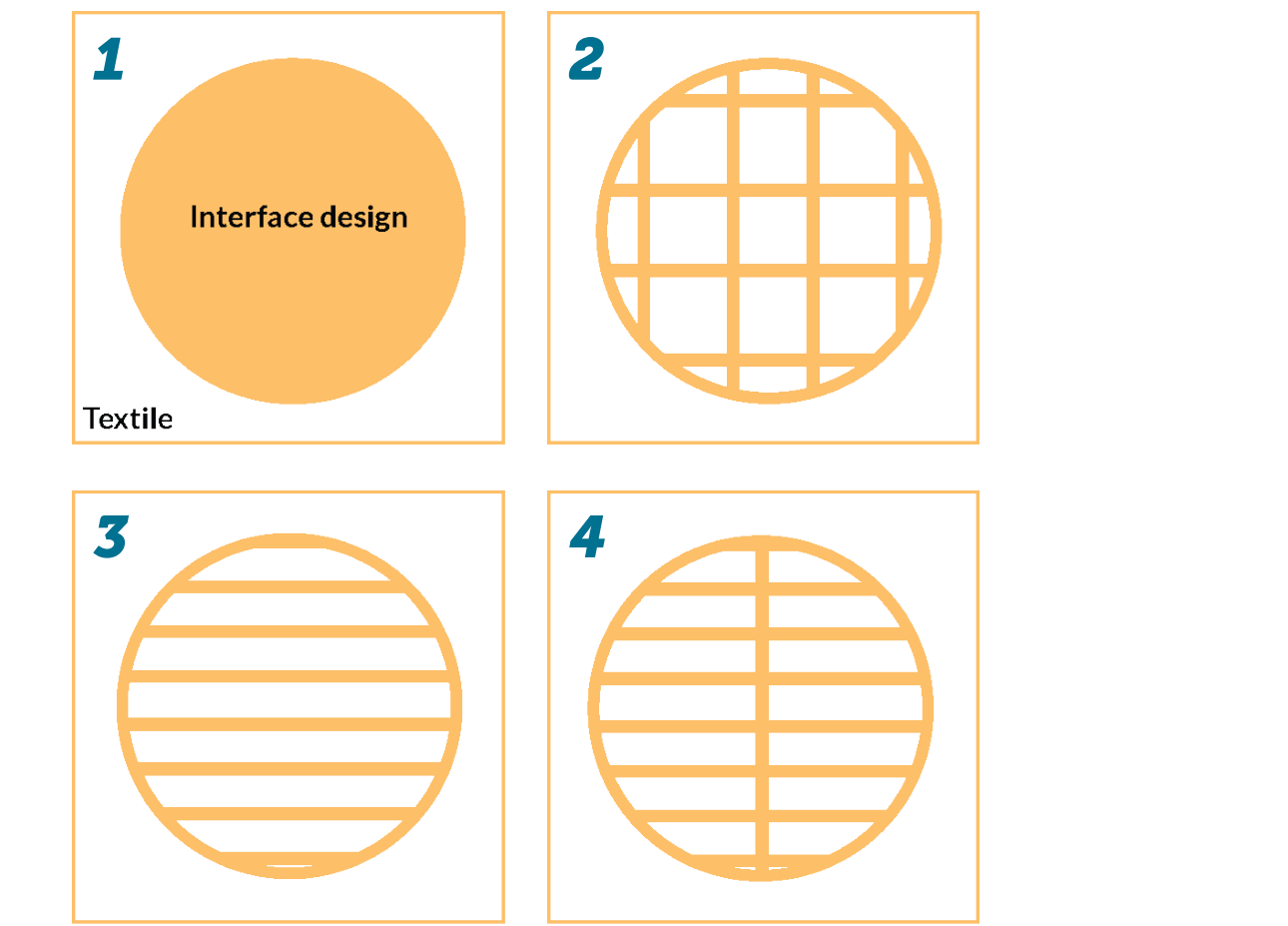


Figure 33. Schematic representation of the four interface design variations (middle layers): Design 1, 2, 3 and 4

Table 9. the design, infill and surface area of the four design variations of the middle layers.

	Dolly	Design 1	Design 2	Design 3	Design 4
Infill	100%	100%	22%	23%	25%
Line thickness (mm)	-	-	1	1	1
Surface area (mm2)	444,88	14.291,47	3.159,37	3.291,65	3.521,87

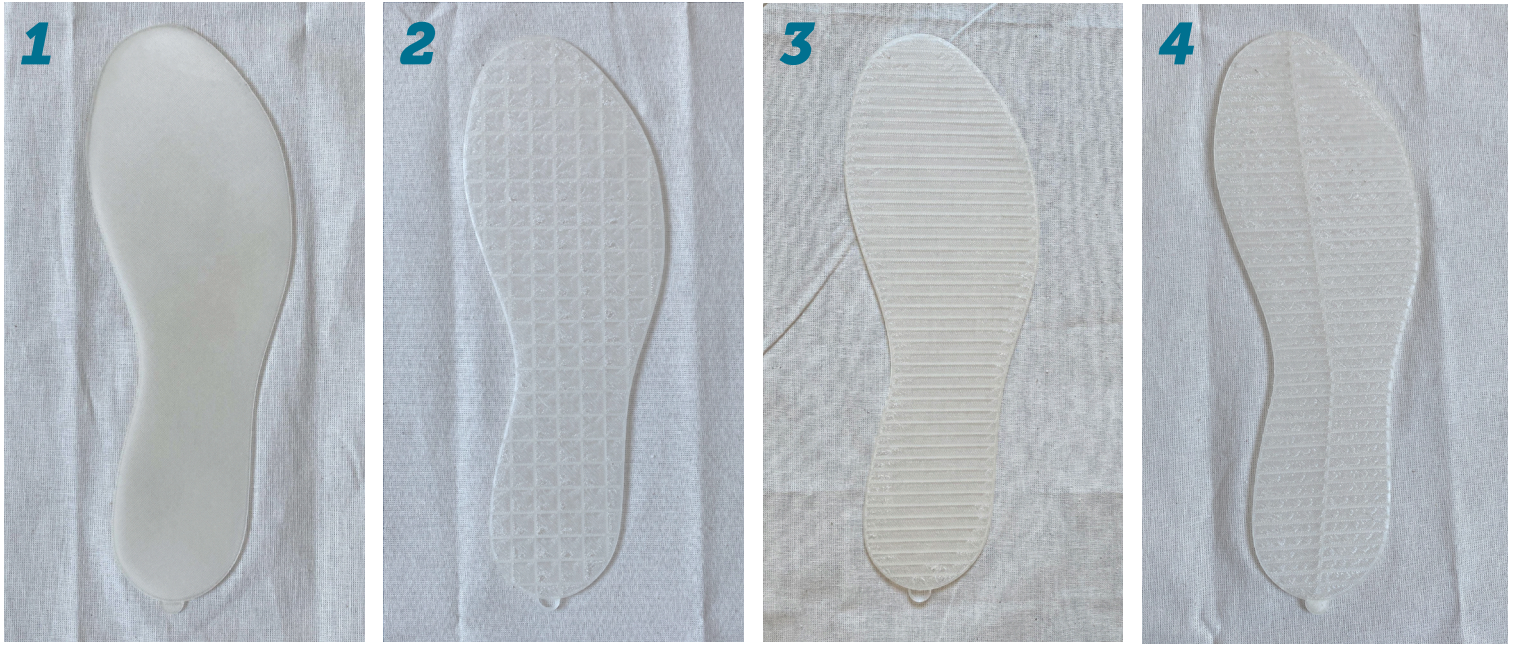


Figure 34. The 3D printed prototypes of the four interface design variations (middle layers): Design 1, 2, 3 and 4

6.2.2 Evaluation setup

The separation test regarding the EoL – test setup “EoL”, is performed at a local temperature of 40oC, based on the findings of the previous experiment (chapter 4). A Steinel heat gun directed towards the prototype applies the heat, which is measured by an RS 1319A K-Type thermocouple. The separation is executed manually in a perpendicular direction (as seen in figure 35). Measurements of the peak separation force are gathered with the usage of a digital force gauge (500N), which is attached to a Toolcraft mini one hand clamp 100x35mm (Model no.: HT03866), that is in turn secured on the textile end alongside the 3D structure, which is held down manually (figures 36-37).

The test representing a possible separation scenario due to repeated loading – test setup “lifetime”, is performed at room temperature. During this test, the prototype undergoes repeated bending in both directions for an approximate curvature radius of 6-10 degrees (as seen in figure 38) until failure. The failure scenarios range from adhesive failure to cohesive failure of the polymer or of the textile substrate. Finally, the gathered measurements are the repetitions before failure.

For both test setups one sample is tested, due to time limitations.

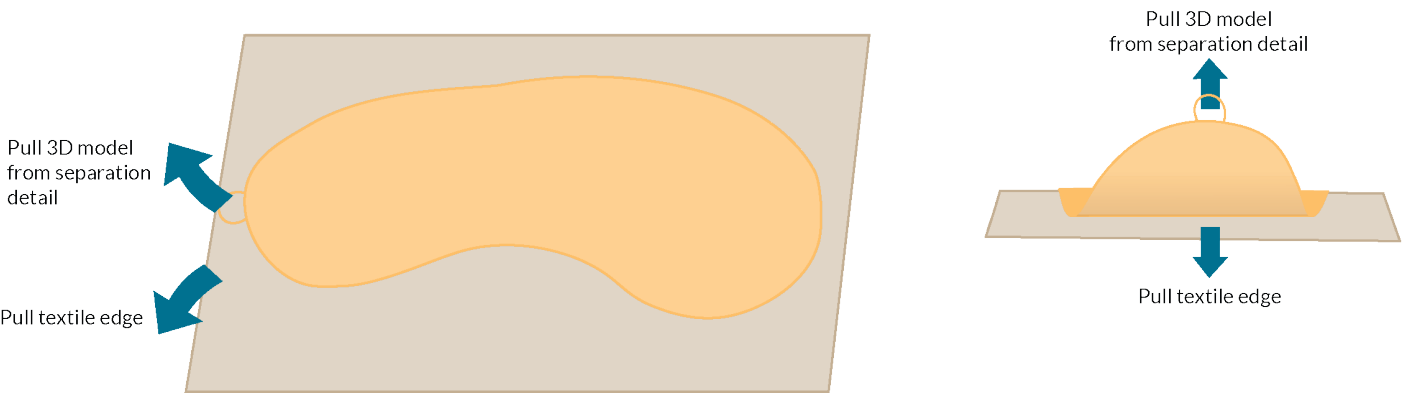


Figure 35. Test setup: “EoL” – the test representing the separation that happens at the EoL of the product which enables PLA and textile recycling.

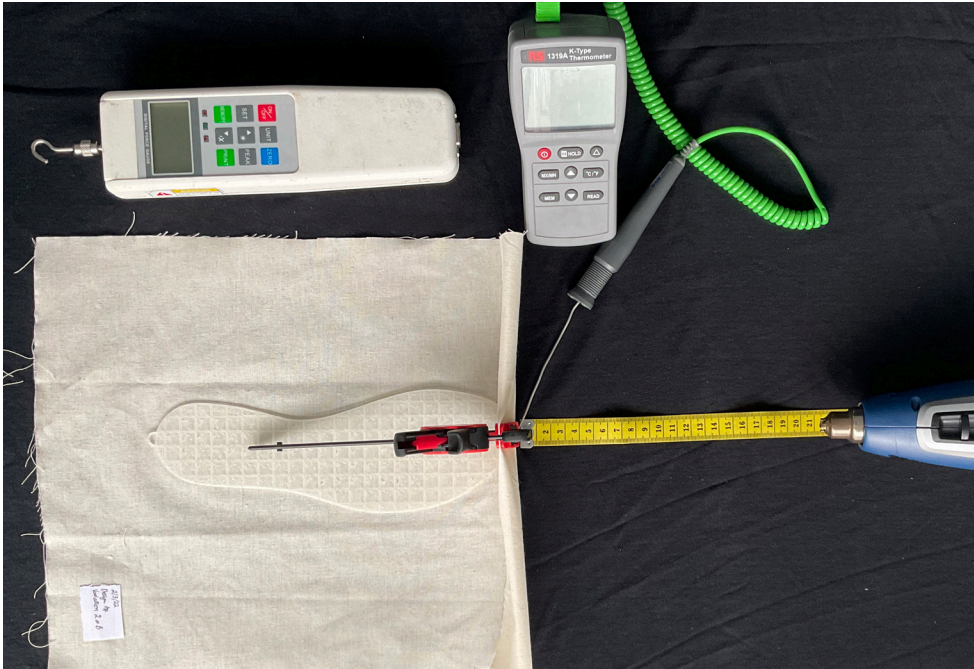


Figure 36. Top view of “EoL” separation test setup.

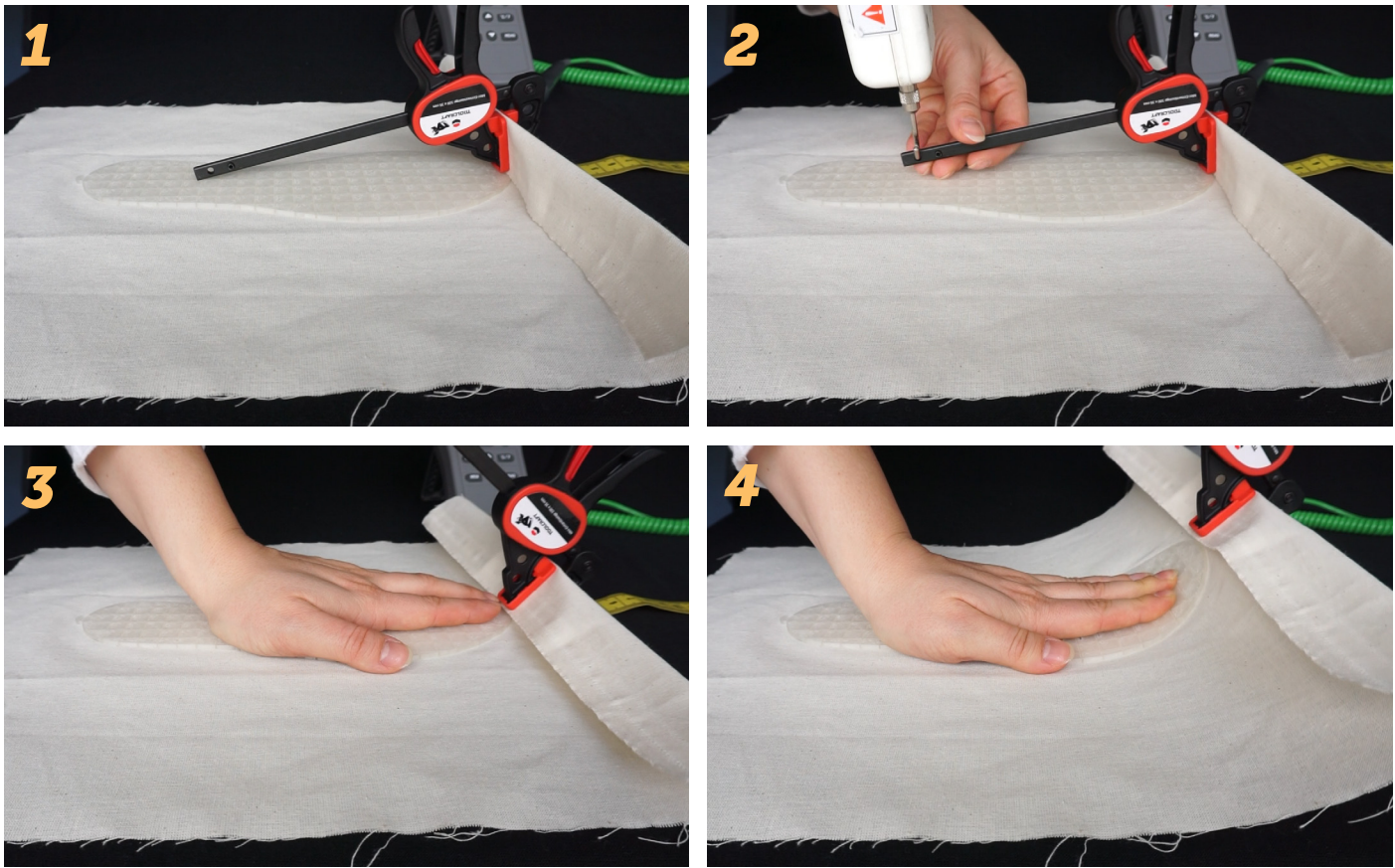


Figure 37. Side view of “EoL” test setup and the measurement of the separation forces.

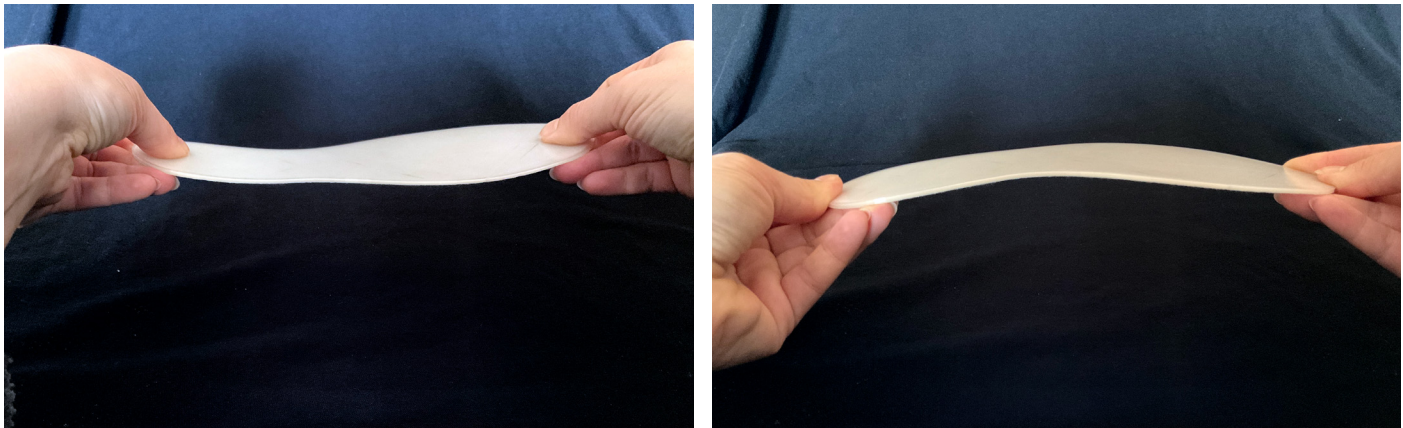


Figure 38. Side view of the “lifetime” test setup, which shows he repeated bending inflicted of the prototype.

6.3
Results and discussion

The results of the separation tests are collected in table 10. Figures 39-40 showcase the prototypes after separation and the failure types that occurred.

The peak forces recorded during the “EoL” separation test show that design 1 resists the highest peak separation forces before failure. However, the surface area (infill) does not solely define the peak forces resistance, because design 2 has the lowest infill and resists the highest peak forces amongst designs 2,3 and 4. Regarding the failure type, design 1 reached one-sided adhesive failure and polymer cohesive failure, possibly due to the strong polymer-textile connections. Additionally, the design with lowest peak separation forces (design 3) reached polymer cohesive failure, that is possibly attributed to the lack of support in the perpendicular direction.

As for the “lifetime” separation test, similarly to the “EoL” test, design 1 resists the most repetitions in contrast with the other designs (2,3 and 4). The low repetition resistance for designs 2,3 and 4 could be attributed to

the degree of deformation that the mid-sole undergoes in the experiment. During this test, the critical failure that is observed for all the designs is polymer cohesive failure and one-sided adhesive failure at the layers below the textile. This means that the polymer mid-sole failed instead of its connection to the textile. Last but not least, for designs 1,3 and 4 cohesive failure happened only once, while for design 2, multiple fracture occurred.

Finally, it is important to mention the possible errors that could happen during the separations. This test setup is not very precise, because of the human factor, so it is suggested to design an experimental setup that rules out the human component, for more accurate and reliable results. Also, producing the models is time consuming, thus only 1 sample per design variation is tested. Using one sample is very limiting in regards of statistical analysis, so it is suggested in the future to select two designs and repeat the process with at least 5 samples. For the full possible error overview, see table 11.

Table 10. Each design’s performance in regards to peak separation force at the “EoL” separation test and to loading repetitions at the “lifetime” separation test, along with the failure types which occurred at every occasion.

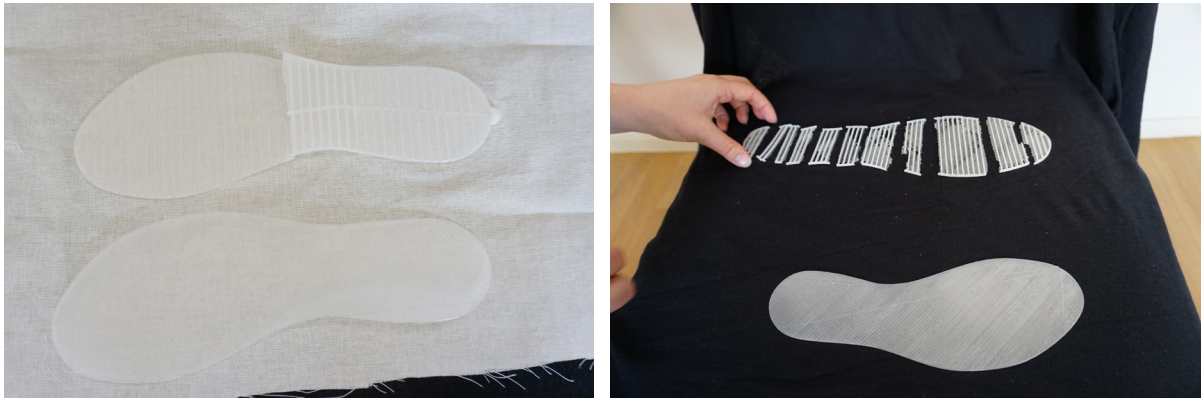
Design - Infill	“EoL” Separation Test		“Lifetime” separation test	
	Peak separation force	Failure type	Loading Repetitions	Failure type
1 – 100%	51,0 N	One-sided adhesive failure + polymer cohesive failure	198	Polymer cohesive failure + one-sided adhesive failure
2 – 22%	41,7 N	Adhesive failure	31	Polymer cohesive failure + one-sided adhesive failure
3 – 23%	18,3 N	Adhesive failure + polymer cohesive failure	23	Polymer cohesive failure + one-sided adhesive failure
4 – 25%	27,1 N	Adhesive failure	23	Polymer cohesive failure + one-sided adhesive failure

Table 11: Possible errors during the separation tests.

“EoL” separation test	1/ The heating around the prototype is not uniform.
	2/ Perpendicular forces could be mixed with shear forces because the two components of the separation (polymer and textile) are not secured in their position.
	3/ During the test there is no control of the separation direction.
“Lifetime” separation test	4/ In reality, sole bending on the z-axis during walking happens in a lot of different positions along the y-axis and not just the centre.
	5/ The force of bending could vary between repetitions.
	6/ The bending angle might differ between repetitions.
	7/ During the test there is no control of the bending direction.
Analysis	8/ The limited number of samples can lead to misinformation.



Figure 39. The “EoL” separation test setup led to adhesive failure for all the designs. For design 1 (image 1), one-sided adhesive separation occurred at the layers below the textile (bottom layer type). Designs 2 (image 2), 3 (image 3) and 4 (image 4) resulted into material separation due to two-sided adhesive failure. During separation, polymer cohesive failure occurred for designs 1 and 3.



Figures 40. The “lifetime” separation setup led to polymer cohesive failure at the layers above the textile (middle and top layer types) and one-sided adhesive failure for the layers below the textile (bottom layer type). For designs 1,2 and 4 the cohesive failure happened once, close to the centre of the 3D structure (left image), while for design 3 it happened multiple times along the 3D structure (right image).

6.4

Conclusions

Adhesive failure is the desired type of failure in regards to separation and recycling, because it releases the two materials from each other, especially when it is two-sided, and allows them to follow their individual recycling paths (fabric recycling or textile reuse and polymer recycling). In the occasions that one-sided adhesive failure happens, additional measures need to be taken to fully separate the remaining polymer layers from the textile.

When one-sided adhesive failure happens, the layers that get separated from the textile are always the layers below the textile (bottom layer type). This happens because the bottom layers attach to the textile after being printed, in contrast with the layers above it (middle and top layer types) which adhere to the textile during printing. To further explain, the bottom layers are close to the polymer glass transition temperature due to the platform temperature and the layers above the textile are at the extruder temperature (60 and 200 °C respectively), which causes the polymer to be in a much lower viscosity while at the same time being pressed against the textile. As discussed in chapter 3, lower viscosity enables deeper penetration to the textile voids and stronger adhesion.

Finally, polymer cohesive failure is undesirable failure type because similarly to substrate cohesive failure, it does not separate the materials and at the same time complicates recycling. Even worse, when there are multiple locations of cohesive failure (design 3 - figure 40), it is nearly impossible to separate the materials thoroughly.

During the “EoL” separation test, the prototypes failed either by reaching one-sided (design 1) or two-sided adhesive failure (designs 2, 3 and 4) and sometimes polymer cohesive failure (designs 1 and 3). In contrast with experimental testing on polymer-textile interface, there is no textile substrate cohesive failure, which is possibly attributed to the selection of textile A. The “lifetime” separation test resulted into polymer cohesive failure and one-sided adhesive failure in all cases.

Insight 1: Increased surface area leads to strong, but irreversible polymer-textile bonds.

Overall, design 1 provides the strongest adhesion due to the large surface area, but it does so in an irreversible way. The critical failures it reached at both separation tests are not desired.

Insight 2: Interface design as an influential parameter for separation.

Designs 2, 3 and 4 have similar surface area (22%, 23% and 25% of design 1 respectively). However, the peak forces received in descending order are for: design 2, 4 and 3. That indicates the influence on adhesion of another parameter, which is the interface design. Even though design 2 has the least surface area, it forms the stronger polymer-textile bond. Possibly, the lines at both directions instead of one (design 3) provided better stability and thus resisted to separation.

Insight 3: The condition to achieve reversible polymer-textile bonds is to use 3D structures and textiles that are more resistant to separation forces than their bond.

Despite the increased peak forces of designs 2 and 4, in regards to separation and recyclability, the failure type that occurs during the separation process is more important than the peak forces. These two designs have reached two-sided adhesive failure without compromising the quality of the textile or complicating separation through cohesive failure. Therefore, to achieve reversible polymer-textile bonds, the cohesive connections of adhesive and substrate must be stronger than the adhesive polymer-textile bond, so that the bond fails before the materials.

Insight 4: Shear forces present in polymer-textile separation for footwear.

Furthermore, from the results it is clear that the peak forces recorded are lower than the peak forces in the experimental polymer-textile separation (dolly as 3D structure). This is possibly attributed to the current experimental setup, where shear forces are likely to be applied instead of tensile forces. Even though this is possibly a more accurate force application in comparison to tensile forces, the peak forces between the two experiments cannot be compared.

Insight 5: Lifetime failure affecting EoL.

During the “lifetime” separation test, the critical failure that is observed is cohesive failure, instead of adhesive failure. This means that the polymer mid-sole failed instead of its bond to the textile. While this shows that the polymer-textile bond is less likely to separate during use, at EoL the mid-soles that polymer cohesive failure has occurred previously will have complicated separation and recycling. Thus, it is important to overcome failures related to the materials structure (3D print or textile).

Reflecting on the third sub-question, the parameters that influence adhesion can be combined with the parameters that favour separation through the utilization of interface design in a way that it allows for separation and provides a stable polymer-textile bond during use, so that it is resistant to repeated loading. The interface design regulates adhesive connection by distributing the surface area, which is the area available for contact between polymer and textile. The amount of penetration and the contact are consequently defined by the area available for contact (surface area), the textile roughness and the polymer viscosity. While textile roughness is constant once a specific textile is selected, polymer viscosity varies depending on the local temperature conditions and can therefore enable separation. However, the separation actually happens, only when the polymer-textile interface reaches adhesive failure. The difference between failure types is dependent on the materials' individual cohesive bonds and the polymer-textile adhesive bond that can be tuned through designing the interface. This is the extent of the connection design performed in this project (chapter 2.3)

7.

Reflection & Recommendations

7.1

Critical reflection

This exploration started with an envisioned material journey. Although a lot of progress has been made in this direction, the way to realizing material circularity is long and not fully explored. The first step towards the envisioned material journey is achieving material separation at the EoL of the product through the creation of reversible polymer-textile bonds, so that in EoL the materials can be individually recycled. Inspired from DfD, a framework for separation is developed. At this chapter, the steps and decisions taken following this framework to reach separation are criticized.

The separation framework begins with establishing a disassembly plan, which is represented by the envisioned material journey and enabled by the separation happening through heat deformation. For this to happen, the recovered materials need to be in condition suitable for recycling, which is not guaranteed for PLA after the separation, since in figure 25 it is evident that the polymer has residual of textile fibres. Low purity of the PLA stream may affect the PLA recycling (Beefink et al., 2021). Additionally, the circulation of materials in loop 1 (figure 5) is not proven through the exploration, as the materials used are not recycled and is thus unknown how recycled materials would respond to the production process of 3DP and if the properties of the connection remain the same. What's more, in case fabric recycling is not possible and fibre recycling is required, it results into either shortened cotton fibres (mechanical recycling), which are unsuitable for apparel applications or other types of fibres like viscose and lyocell (chemical recycling) (Harmsen & Bos, 2020). A fibre more suitable for fibre recycling is wool and could be an alternative to cotton.

Besides material recycling properties, material selection should also be influenced by mechanical properties. Mechanical properties (such as tensile modulus) need to be considered to ensure reversible polymer-textile bonds. Therefore, substituting cotton with a stronger material while maintaining the fabrication method of textile B (larger pore sized textile) would result into a more force resistant polymer-textile interface than the ones explored in the project. Furthermore, flexible polymers could prevent the cohesive failure that happened in the "lifetime" separation tests and improve comfort during usage.

Regarding the connection design, there are aspects that could be improved or further researched. In this project textile pore size is researched as a textile roughness indicator. Nonetheless, textile pore frequency combined with textile pore size is a stronger indicator of the textile roughness and needs to be taken into account. Another aspect to improve would be implementing higher local separation temperatures to ease separation for the prototypes that reached cohesive failure (textile substrate or polymer). Moreover, the separation tests need to be carried out in a consistent and controlled manner to ensure quality of the separated materials. Currently, the type of forces measured in the experiments might not be very accurate. Except for that, the "EoL" separation test is not 100% consistent with the tensile testing done perviously, which means that the peak force measurements from the dollies and the footwear mid-soles cannot be directly compared. In real usage conditions, shear forces are also present. The test must be repeated at least 5 times in a controlled environment for credibility too. The 3D structure can also afford improvements.

Regarding the influence of usage conditions, a lattice structure especially designed for walking can be a measurement to avoid the repetitive fraction that happened in "lifetime" separation tests and to address realistic footwear mid-sole scenarios. Finally, the separation should be facilitated by a design detail, because at this stage separation initiation was challenging and might have tempered with the results.

Last but not least, there are some concerns about the footwear application. Mid-sole is most of the time accompanied by an outsole, which is not addressed in this project, and always attached to the upper shoe textile, which is partly addressed in terms of connection to the mid-sole but not as a functional product part itself. What is more, in the polymer-textile interface should be tested in usage conditions further, as it is evident that they influence EoL as well ("lifetime" separation test). Lastly, 3DP is not equivalent to mass manufacture: it is slow and expensive. The average sole takes seven hours to print. Thus, there might be difficulties to continue with this application.

7.2

Future Recommendations

There are some steps that could be taken in the future, to overcome the issues mentioned previously. Firstly, to improve the separation tests, an experimental setup that is at least partly automated needs to be designed, so that separation is performed in a controlled and consistent manner and repeat it for at least 5 times to ensure reproducibility. To come a step closer to the envisioned material journey, recycled materials need to be tested in the same separation conditions ("EoL" and "lifetime") to investigate their response to separation and if it coincides with the virgin materials.

For the sake of improving the application of polymer-textile interfaces on footwear, the tested designs of the mid-sole middle layers should be replaced by lattice

structures and flexible polymers need to be tested instead of stiff PLA. Overall, in applications the form fitting of the products needs to be designed as well. Specifically for footwear, the upper shoe textile can be shaped to fit the user by 3DP a few layers onto the textile according to the desired shape-change (figure 41). Lastly, the fabrication of responsive textiles such as wool or heat responsive fibres can create a foldable shoe that would activate itself by coming in contact with the 3D printed polymer structure.

Finally, the separation framework can facilitate the experimentation and testing of materials and methods and can be applied to other materials to create a material library that would broaden the scope of product applications.

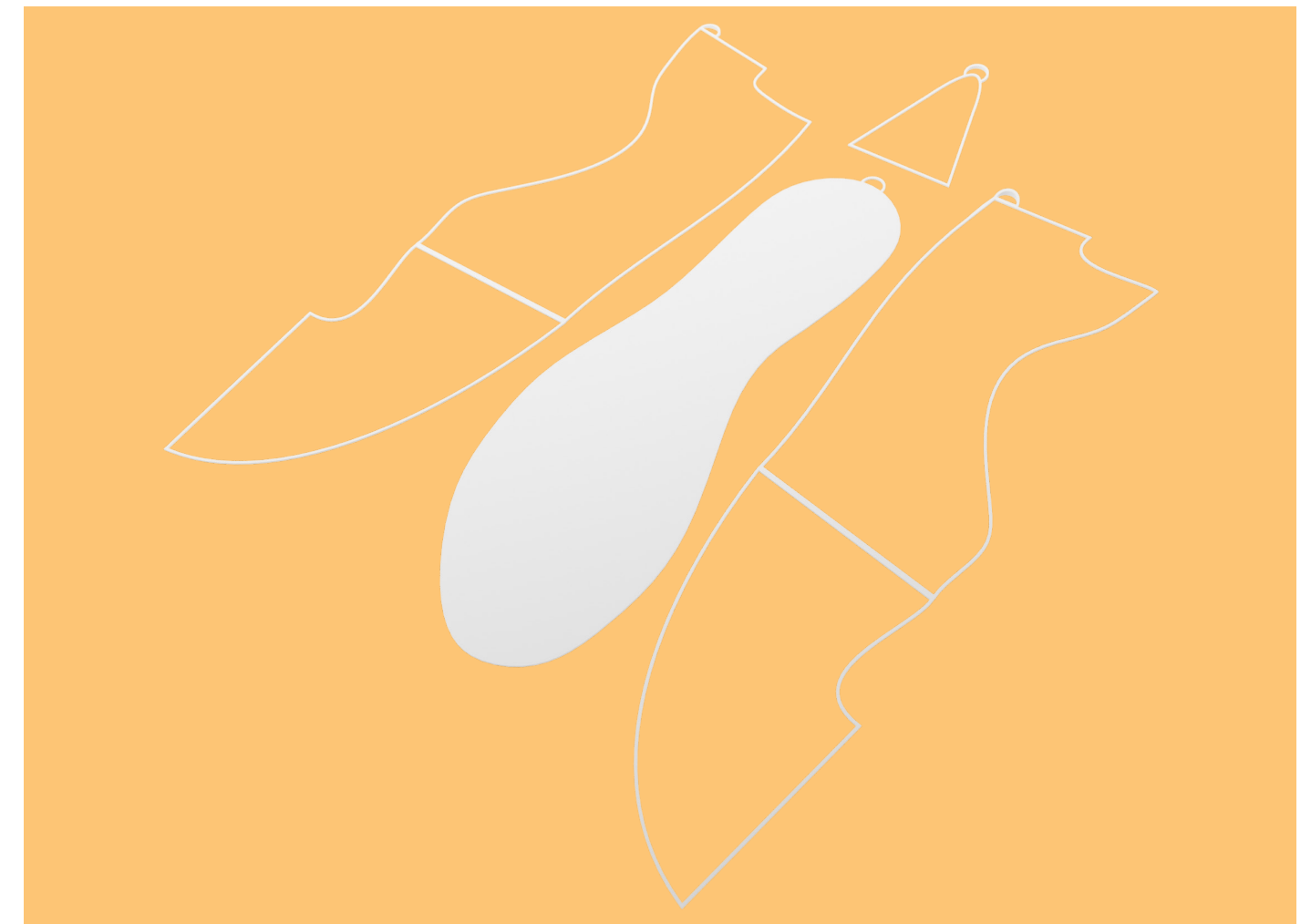


Figure 41. A vision of how 3D printed structures would be placed to shape the textile. Details for separation and structures that would aid shaping are shown.



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References

- [1] Abu, M., Nur-E, A., Wahid, M., Farid, A., & Uddin, M. (2017). Waste management & quality assessment of footwear manufacturing industry in bangladesh: an innovative approach. *International Journal of Engineering and Management Research*, 7(4), 402–407. www.ijemr.net
- [2] Awaja, F., Kelly, G., Fox, B. L., & Pigram, P. (2009). Adhesion of polymers. January 2018. <https://doi.org/10.1016/j.procpolymsci.2009.04.007>
- [3] Beeftink, M., Vendrik, J., Bergsma, G., & Veen, R. van der. (2021). PLA sorting for recycling PLA sorting for recycling.
- [4] Dissanayake, D. G. K., & Weerasinghe, D. (2021). Towards Circular Economy in Fashion: Review of Strategies, Barriers and Enablers. *Circular Economy and Sustainability*. <https://doi.org/10.1007/s43615-021-00090-5>
- [5] Doubrovski, Z., Stokhuijzen, D., Aberle, N., Herpen, I. van, Schuddeboom, P., & Verlinden, J. (2017). fabricating the Foliage Dress: Computational Design in Couture. *Fabricating the Foliage Dress: Computational Design in Couture*, 1281–1284.
- [6] Ellen Macarthur Foundation. (2017). A New Textiles Economy: Redesigning fashion's future. Retrieved from <https://ellenmacarthurfoundation.org/a-new-textiles-economy>
- [7] Faste, T., & Faste, H. (2011). Demystifying “design research”:
- [8] Gorlachova, M., & Mahltig, B. (2021). 3D-printing on textiles – an investigation on adhesion properties of the produced composite materials. *Journal of Polymer Research*, 28(6), 1–10. <https://doi.org/10.1007/s10965-021-02567-1>
- [9] Grimmelsmann, N., Kreuziger, M., Korger, M., Meissner, H., & Ehrmann, A. (2018). Adhesion of 3D printed material on textile substrates. *Rapid Prototyping Journal*, 24(1), 166–170. <https://doi.org/10.1108/RPJ-05-2016-0086>
- [10] Harmsen, P., & Bos, H. (2020). Textiles for Circular Fashion.
- [11] Koen, P., Ajanian, G., Burkart, R., Clamen, A., Davidson, J., D'Amore, R., Elkins, C., Herald, K., Incorvia, M., Johnson, A., Karol, R., Seibert, R., Slavejko, A., & Wagner, K. (2001). Providing clarity and a common language to the “fuzzy front end.” *Research Technology Management*, 44(2), 46–55. <https://doi.org/10.1080/08956308.2001.11671418>
- [12] Kozior, T., Blachowicz, T., & Ehrmann, A. (2020). Adhesion of three-dimensional printing on textile fabrics: Inspiration from and for other research areas. *Journal of Engineered Fibers and Fabrics*, 15. <https://doi.org/10.1177/1558925020910875>
- [13] Kozior, T., Döpke, C., Grimmelsmann, N., Juhász Junger, I., & Ehrmann, A. (2018). Influence of fabric pretreatment on adhesion of three-dimensional printed material on textile substrates. *Advances in Mechanical Engineering*, 10(8), 1–8. <https://doi.org/10.1177/1687814018792316>
- [14] Kycia, A. (2018). Material Form Finding of modular Textile Structures. 44(8). <https://doi.org/10.1088/1751-8113/44/8/085201>
- [15] Lellis, B., Fávaro-Polonio, C. Z., Pamphile, J. A., & Polonio, J. C. (2019). Effects of textile dyes on health and the environment and bioremediation potential of living organisms. *Biotechnology Research and Innovation*, 3(2), 275–290. <https://doi.org/10.1016/j.biori.2019.09.001>
- [16] Loh, G. H., Sotayo, A., & Pei, E. (2021). Development and testing of material extrusion additive manufactured polymer–textile composites. *Fashion and Textiles*, 8(1). <https://doi.org/10.1186/s40691-020-00232-7>
- [17] Lussenburg, K., Velden, N. Van Der, Doubrovski, Z., Geraedts, J., & Karana, E. (2014). Designing 3D Printed Textiles. *Proceedings of the 5th International Conference on Additive Technologies*, 74–81. <http://repository.tudelft.nl/view/ir/uuid:29efd856-3d07-43ff-9ae6-338a6dcee84b/>
- [18] Malengier, B., Hertleer, C., Cardon, L., & Langenhove, L. . (2018). 3D Printing on Textiles: Testing of Adhesion. *Journal of Fashion Technology & Textile Engineering*, s4(January). <https://doi.org/10.4172/2329-9568.s4-013>
- [19] Melnikova, R., Ehrmann, A., & Finsterbusch, K. (2014). 3D printing of textile-based structures by Fused Deposition Modelling (FDM) with different polymer materials. *IOP Conference Series: Materials Science and Engineering*, 62(1). <https://doi.org/10.1088/1757-899X/62/1/012018>
- [20] Meyer, P., Döpke, C., & Ehrmann, A. (2019). Improving adhesion of three-dimensional printed objects on textile fabrics by polymer coating. *Journal of Engineered Fibers and Fabrics*, 14(February 2020). <https://doi.org/10.1177/1558925019895257>
- [21] Moldoveanu, S. C., & David, V. (2017). RP-HPLC Analytical Columns. Selection of the HPLC Method in Chemical Analysis, 279–328. <https://doi.org/10.1016/B978-0-12-803684-6.00007-X>
- [22] Morton, W. E., & Hearle, J. W. S. (2008). Physical Properties of Textile Fibres: Fourth Edition. In *Physical Properties of Textile Fibres: Fourth Edition*. <https://doi.org/10.1533/9781845694425>
- [23] Mpofu, N. S., Mwasiagi, J. I., Nkiwane, L. C., & Njuguna, D. (2019). Use of regression to study the effect of fabric parameters on the adhesion of 3D printed PLA polymer onto woven fabrics. *Fashion and Textiles*, 6(1). <https://doi.org/10.1186/s40691-019-0180-6>

[24] Nijland, T. G., & Larbi, J. A. (2010). Microscopic examination of deteriorated concrete. Non-Destructive Evaluation of Reinforced Concrete Structures: Deterioration Processes and Standard Test Methods, 137–179. <https://doi.org/10.1533/9781845699536.2.137>

[25] Novakova-Marcincinova L., Novak-Marcincin J., Barna J. and Torok J., “Special materials used in FDM rapid prototyping technology application,” 2012 IEEE 16th International Conference on Intelligent Engineering Systems (INES), 2012, pp. 73-76, doi: 10.1109/INES.2012.6249805.

[26] Östlund, Å., Wedin, H., Bolin, L., Berlin, J., Jönsson, C.. (2015) Textilåtervinning: Tekniska möjligheter och utmaningar [Textile recycling – technical opportunities and challenges] Naturvårdsverket rapport, 6685. Retrieved from <http://www.naturvardsverket.se/Om-Naturvardsverket/Publikationer/ISBN/6600/978-91620-6685-7/> (Accessed June 2017)

[27] Oyón-Calvo, J., Cazón-Martín, A., Rodríguez-Ferradas, M. I., Francés-Morcillo, L., Matey-Muñoz, L., & Morer-Camo, P. (2019). Additive manufacturing on textiles with low-cost extrusion devices: Adhesion and deformation properties. Dyna (Spain), 94(3), 221–225. <https://doi.org/10.6036/8893>

[28] Pei, E., Loh, G. H., Harrison, D., De Amorim Almeida, H., Verona, M. D. M., & Paz, R. (2017). A study of 4D printing and functionally graded additive manufacturing. Assembly Automation, 37(2), 147–153. <https://doi.org/10.1108/AA-01-2017-012>

[29] Pei, E., Shen, J., & Watling, J. (2015). Direct 3D printing of polymers onto textiles: Experimental studies and applications. Rapid Prototyping Journal, 21(5), 556–571. <https://doi.org/10.1108/RPJ-09-2014-0126>

[30] Pike, Roscoe A.. “adhesive”. Encyclopaedia Britannica, 12 Aug. 2021, <https://www.britannica.com/technology/adhesive> . Accessed 23 September 2021.

[31] Riley, A. (2012). Plastics manufacturing processes for packaging materials. Packaging Technology, 310–360. <https://doi.org/10.1533/9780857095701.2.310>

[32] Rivera, M. L., Moukperian, M., Ashbrook, D., Mankoff, J., & Hudson, S. E. (2017). Stretching the bounds of 3D printing with embedded textiles. Conference on Human Factors in Computing Systems - Proceedings, 2017-May(October), 497–508. <https://doi.org/10.1145/3025453.3025460>

[33] Roos, S., Sandin, G., Peters, G., Spak, B., Schwarz Bour, L., Perzon, E., & Jönsson, C. (2019). Guidance for Fashion Companies on Design for Recycling. November. <https://doi.org/10.13140/RG.2.2.34374.22083>

[34] Sabantina, L., Kinzel, F., Ehrmann, A., & Finsterbusch, K. (2015). Combining 3D printed forms with textile

structures - Mechanical and geometrical properties of multi-material systems. IOP Conference Series: Materials Science and Engineering, 87(1). <https://doi.org/10.1088/1757-899X/87/1/012005>

[35] Sanatgar, R. H., Campagne, C., & Nierstrasz, V. (2017). Investigation of the adhesion properties of direct 3D printing of polymers and nanocomposites on textiles: Effect of FDM printing process parameters. Applied Surface Science, 403, 551–563. <https://doi.org/10.1016/j.apsusc.2017.01.112>

[36] Sandin, G., & Peters, G. M. (2018). Environmental impact of textile reuse and recycling – A review. Journal of Cleaner Production, 184(March), 353–365. <https://doi.org/10.1016/j.jclepro.2018.02.266>

[37] Scott, J. (2013). Hierarchy in knitted forms: Environmentally responsive textiles for architecture. ACADIA 2013: Adaptive Architecture - Proceedings of the 33rd Annual Conference of the Association for Computer Aided Design in Architecture, 361–366.

[38] Spahiu, T., Grimmelsmann, N., Ehrmann, A., Piperi, E., & Shehi, E. (2017). Effect of 3D Printing on SCM. Lecture Notes in Mechanical Engineering, November, 157–164. https://doi.org/10.1007/978-981-15-8542-5_14

[39] Suffian, S., Dzombak, R., & Mehta, K. (2016). Future directions for nonconventional and vernacular material research and applications. Nonconventional and Vernacular Construction Materials, 63–80. <https://doi.org/10.1016/B978-0-08-100038-0.00003-2>

[40] thredUP. (2022). 2021 Resale Report. Retrieved from <https://www.thredup.com/resale/#resale-industry>

[41] van Schaik, A., & Reuter, M. A. (2014). Material-Centric (Aluminum and Copper) and Product-Centric (Cars, WEEE, TV, Lamps, Batteries, Catalysts) Recycling and DfR Rules. Handbook of Recycling: State-of-the-Art for Practitioners, Analysts, and Scientists, 307–378. <https://doi.org/10.1016/B978-0-12-396459-5.00022-2>

[42] Vanegas, P., Peeters, J. R., Cattrysse, D., Tecchio, P., Ardente, F., Mathieux, F., Dewulf, W., & Duflou, J. R. (2018). Ease of disassembly of products to support circular economy strategies. Resources, Conservation and Recycling, 135(July), 323–334. <https://doi.org/10.1016/j.resconrec.2017.06.022>

[43] Wypych, G. (2018). Mechanisms of Adhesion. Handbook of Adhesion Promoters, 5–44. <https://doi.org/10.1016/b978-1-927885-29-1.50004-3>

Appendix A - Table overview with parameters

The following table summarises the outcome of the literature research about adhesion of polymer-textile interfaces. The second column lists all the influential parameters and the first column the category they belong to. The column titled: impact on adherence, describes the relationship of the parameter and adherence. There are

two possible answers, direct and inversely proportional. Then, based on the research there are suggested properties and their reference. Finally, the last column lists other parameters that can be influenced by potential changes of this parameter.

↑↑ : This symbol means that the parameter is directly proportional with the polymer-textile adhesion.

↑↓ : This symbol means that the parameter is inversely proportional with the polymer-textile adhesion.

Parameter Category	Parameter	Impact on Adherence	Suggested Property	Reference	Parameter Dependence
Production Method					
	Process	-	FDM	(All papers)	-
Printing setting (PP)	Z-distance	↑↓	0 0.2 below textile surface	(Oyón-Calvo et al., 2019) (Grimmelsmann et al., 2018)	Textile thickness
>>	Printing / Extruder Temperature	↑↑	10-30 °C over suppliers' average recommendation	(Gorlachova & Mahltig, 2021)	Polymer viscosity Polymer properties
>>	Platform / Printing Bed Temperature	↑↑	10-40 °C over suppliers' average recommendation	(Gorlachova & Mahltig, 2021)	Polymer viscosity Polymer properties
>>	Printing Speed	↑↓	1 st : 0.8-1.0 m/min = 2mm/sec 2 nd : 3.3 m/min = 6.5mm/sec 20 mm/sec 45 mm/sec	(Gorlachova & Mahltig, 2021) (Loh et al., 2021)	Polymer properties Time
>>	Layer Height	↑↓	>0.2 mm	(Spahiu et al., 2017)	Contact area
>>	Polymer Flow	-	100%	(Loh et al., 2021; Spahiu et al., 2017)	-
>>	Extrusion Width	-	0.4	-	-
>>	Infill	-	Rectilinear, 100%	(Loh et al., 2021)	-
	Stabilization	-	Attachment with clips or double-sided tape	(Oyón-Calvo et al., 2019; Rivera et al., 2017)	Flexibility Stretchability Compression
	Contact Area	↑↑	-	-	Polymer Viscosity Layer Height Extrusion Width Pore size
Polymer					
	Filament Material	-	PLA Nylon	(Loh et al., 2021; Pei et al., 2017; Rivera et al., 2017)	Extrusion Temperature Polymer Viscosity Decomposition Temperature

Appendix B - Initial explorations (1)

The first step of the experimentation is to prototype using different textiles with the same filament, in order to explore the possibilities, understand the interaction between the materials themselves and the process and finally identify sweet spots for further prototyping. The timespan spent during this experimentation is around 20 days and it can be considered as the first part of the development process. Following, the method, results and conclusions will be discussed.

Textile A
The pore size of this textile is a limiting factor for polymer – textile adhesion. The extruded polymer does not flow through the pores and therefore the bottom layer detaches from the textile spontaneously. However, if the textile is ironed in a high ironing setting (linen) before being placed on the printing bed and coming in contact with the first printed polymer layers (step 4), adhesion with the bottom layers is improved significantly and the process results into a successful print.

Textile B
The increase of the pore size contributed to the adhesion of the two materials like suggested from the literature research. It is clear that printing with textile B is an easier process compared to textile A (figures XX). This however can complicate the separation of the materials.

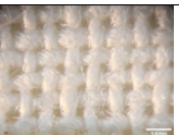
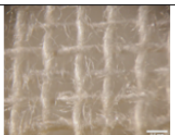
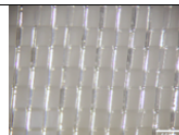

Textile C
When natural fibres are heated in high temperatures the fibre decomposes, while polymer based fibres melt (Morton & Hearle, 2008). Which is what happened during the printing process. The polyester textile softened because of the increased temperatures, possibly leading to chemical adhesion. This is not an advantage, since it

makes the delamination and circularity nearly impossible. The yarn thinness and pore size ration (area that PLA flows through) contributed to the adhesion and resulted to very good printing quality.
Textile D
The last textile is tested to investigate knitted materials and their response to the process. What was found during the experimentation is that knitted materials’ low dimensional stability creates an instable environment for the printing nozzle, which can get entangled and refrain from laying material on the textile. The extension of the knitted materials on the printing bed overcomes this problem, without however reaching reliable results that can be easily reproduced.

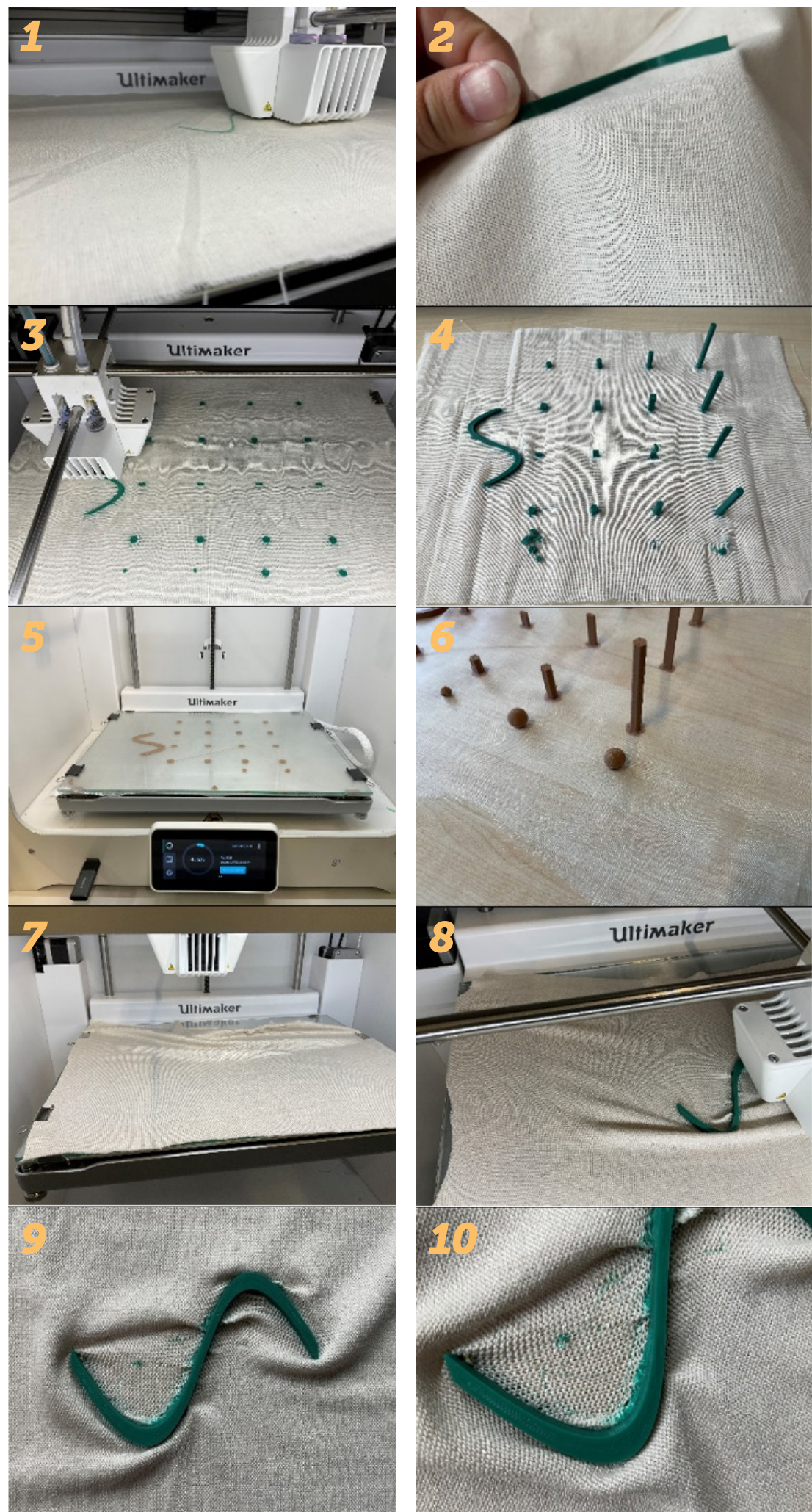
Additional to the before mentioned difficulties, the final print quality is compromised. Despite the improvement with stretching, warp is evident along the vertical axis, which occurred in the direction that the fabric was not stretched. Improvement of the stretching is nearly impossible, since the design of a printer only has 3 free edges to secure the fabric and so, it cannot be stretched along the vertical direction.

The textile variety stems from a lot of different factors, such as fibre properties, fabrication method and textile structure. Therefore, the selected textiles cannot be directly compared. However, the observations can give indications of which parameter is mostly responsible for a specific behaviour. It is important to understand the cause and effect in order to identify relevant properties for achieving delamination. One should bear in mind, that each result is specific to the test performed and it cannot always be generalized for the whole range of knitted textiles, for example.

Table 12: All the textiles that were used in the initial experimentation.

					Information acquired from:
Textile	Textile A – dense cotton	Textile B – sparse cotton	Textile C	Textile D	
Fibre	Cotton	Cotton	Polyester	Viscose 80%, Elastane 20%	Retailer
Fabrication method	Plain weave	Plain weave	Plain weave	Knit	Retailer
Yarn thickness	0,27 ± 0,03 mm	0,20 ± 0,02 mm	0,06 ± 0,01 mm	0,34 ± 0,06 mm	Microscope
Textile thickness	0,25 ± 0,02 mm	0,21 ± 0,03 mm	0,11 ± 0,00 mm	0,59 ± 0,02 mm	Digital Caliper
Pore size	0,17 ± 0,03 mm	0,52 ± 0,08 mm	0,33 ± 0,05 mm	0,32 ± 0,03 mm	Microscope

				(Gorlachova & Mahltig, 2021)	
	Viscosity	↑↓	-	-	Extrusion Temperature Platform Temperature Printing Speed Contact Area Polymer properties Textile roughness Free-standing fibres
Textile					
Fibre	Fibre Type	-	Natural: acrylic and cotton	(Mpofu et al., 2019)	Flexibility Length Weight Hydrophilicity
Fibre	Rate of Absorption / Hydrophilicity	↑↑	Materials with similar rate of absorption are favoured (e.g. Cotton - Nylon)	(Gorlachova & Mahltig, 2021)	Material Compatibility Fabrication method Treatments Polymer Hydrophilicity
Textile structure	Thickness*	↑↑			Z-distance
>>	Roughness	↑↑	-	-	Free standing fibres Polymer viscosity
Fabrication	Fabrication Method	-	-	-	Pore size Dimensional stability Stabilization
>>	Pore size	↑↑	-	-	Polymer viscosity Fabrication method Contact area
>>	Free standing fibres	↑↑	-	-	Roughness Contact area
Treatment	Washing/ coating	Depends on the treatment	-	-	Hydrophilicity Material compatibility
General					
P - T	Material Compatibility	-	-	-	Hydrophilicity Polymer properties Textile properties
PM - P	Time Dependency	-	-	-	Printing speed Chamber temperature Dimensional stability



Figures 42: Printing on textile A after applying heat (1), the result (2). Printing on textile B (3), the result (4). During the process of printing with textile C (5), the result (6). Printing on knitted textile without stretching (7) and with stretching (8). The created warp of knitted textiles being printed on (9,10).

Appendix C - Initial explorations (2)

In this part of the experiments, contact area between textile substrate and polymer is investigated as an influential parameter. The goal is to experiment with the design of the interphase and understand how it affects it. In what degree can we design the interphase? What is a reduced surface area between the two materials that can still achieve good adhesion?

The maximum area is considered to be the surface area of the solid model. An example of a reduced area could be just the outline of the model with a specific thickness. This will be in direct contact with the textile and therefore define the adhesion. The contact area is produced by the same polymer that the model is created, in this case PLA. The idea is in fact, to create a costume-made local infill for the design. This way, there is more design freedom regarding the infill design and a variety of infills can be included in the same solid. In figure XX, the final design of the contact

area is showcased, in order to help with the understanding of the design. The time dedicated to this exploration is around 10 days.

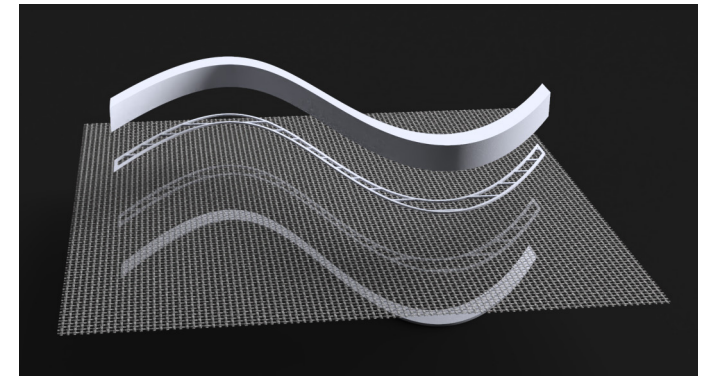
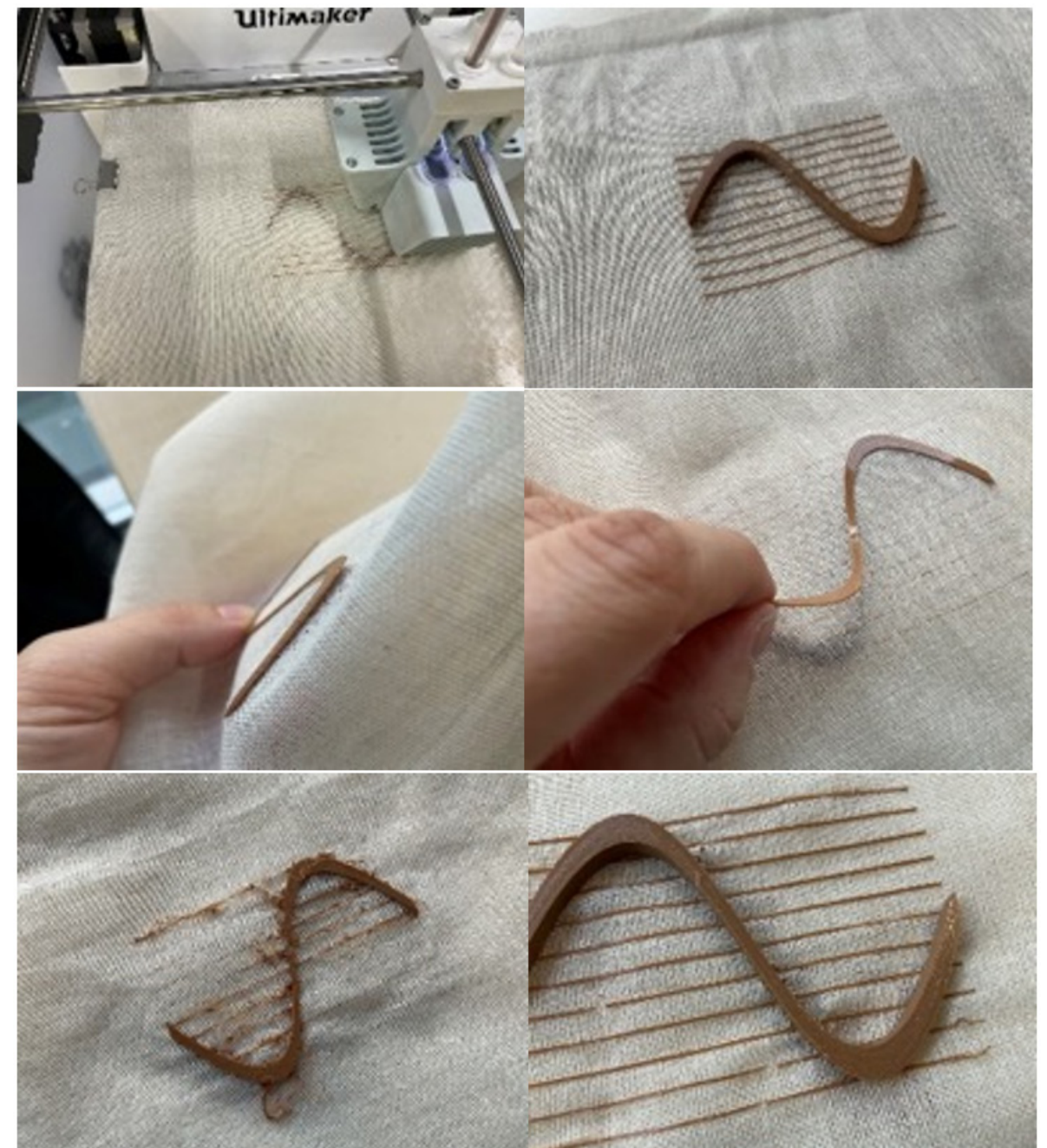


Figure 43: Exploded view of the contact area design between polymer and textile.



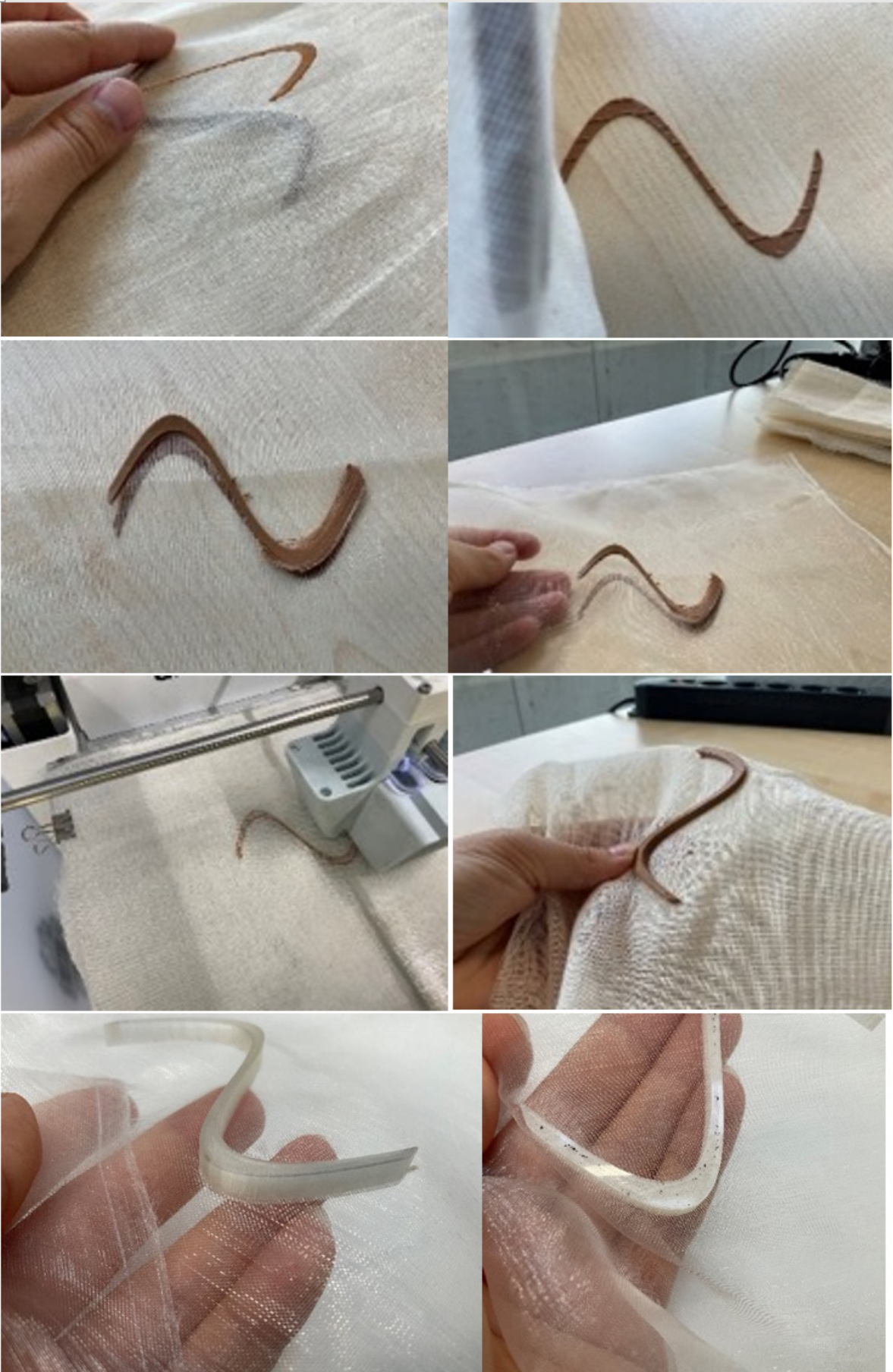


Figure 44. The results of the experimentation using different designs with PLA and textile A, B and C.

Appendix D – Results from the tensile test

Table 13 Perpendicular tensile testing (21oC) results, peak detection force in Newton.

Peak detection (N)			
Prototype A1	94,79203796	Prototype B1	118,7954712
Prototype A2	65,50563812	Prototype B2	72,47153473
Prototype A3	98,82685089	Prototype B3	63,06346893
Prototype A4	118,3696442	Prototype B4	73,85939789
Prototype A5	108,8741455	Prototype B5	76,52011871

Table 14: Perpendicular tensile testing (21oC) results, elongation in millimetre.

Elongation (mm)			
Prototype A1	180,2077	Prototype B1	222,4607
Prototype A2	180,277	Prototype B2	180,0063
Prototype A3	180,2076	Prototype B3	179,9151
Prototype A4	180,0059	Prototype B4	180,0059
Prototype A5	180,0057	Prototype B5	180,2076

Table 15: Perpendicular tensile testing (40oC) results, peak detection force in Newton.

Peak detection (N)			
Prototype A1	93,90512085	Prototype B1	54,11581421
Prototype A2	89,33997345	Prototype B2	55,45710754
Prototype A3	108,1705399	Prototype B3	60,97958755
Prototype A4	81,7542038	Prototype B4	57,82324982
Prototype A5	Measurement failed	Prototype B5	Measurement failed

Table 16: Perpendicular tensile testing (40oC) results, elongation in millimetre.

Elongation (mm)			
Prototype A1	32,46634065	Prototype B1	32,48001165
Prototype A2	32,47999539	Prototype B2	32,48001351
Prototype A3	32,4799919	Prototype B3	32,48054882
Prototype A4	32,48706116	Prototype B4	32,49511558
Prototype A5	Measurement failed	Prototype B5	Measurement failed

Appendix E - Project Brief

DESIGN
FOR OUR
future

TU Delft

IDE Master Graduation

Project team, Procedural checks and personal Project brief

This document contains the agreements made between student and supervisory team about the student's IDE Master Graduation Project. This document can also include the involvement of an external organisation, however, it does not cover any legal employment relationship that the student and the client (might) agree upon. Next to that, this document facilitates the required procedural checks. In this document:

- The student defines the team, what he/she is going to do/deliver and how that will come about.
- SSC E&SA (Shared Service Center, Education & Student Affairs) reports on the student's registration and study progress.
- IDE's Board of Examiners confirms if the student is allowed to start the Graduation Project.

USE ADOBE ACROBAT READER TO OPEN, EDIT AND SAVE THIS DOCUMENT
Download again and reopen in case you tried other software, such as Preview (Mac) or a webbrowser.

STUDENT DATA & MASTER PROGRAMME

Save this form according the format "IDE Master Graduation Project Brief_familyname_firstname_studentnumber_dd-mm-yyyy". Complete all blue parts of the form and include the approved Project Brief in your Graduation Report as Appendix 1 !

family name

Tsoli

4922

initials

D

given name

Dimitra

student number

5163528

street & no.

zipcode & city

country

Netherlands

phone

email

d.tsoli@student.tudelft.nl

Your master programme (only select the options that apply to you):

IDE master(s):

☒ IPD

☐ Dfl

☐ SPD

2nd non-IDE master:

individual programme:

- - (give date of approval)

honours programme:

☐ Honours Programme Master

specialisation / annotation:

☐ Medisign

☐ Tech. in Sustainable Design

☐ Entrepreneurship

Supervisory team **

Fill in the required data for the supervisory team members. Please check the instructions on the right !

** chair

Zjenja Doubrovski

dept. / section:

SDE

** mentor

Ruud Balkenende

dept. / section:

SDE

2nd mentor

organisation:

city:

country:

comments (optional)

Chair should request the IDE Board of Examiners for approval of a non-IDE mentor, including a motivation letter and c.v.

Second mentor only applies in case the assignment is hosted by an external organisation.

Ensure a heterogeneous team. In case you wish to include two team members from the same section, please explain why.

Procedural Checks - IDE Master Graduation

APPROVAL PROJECT BRIEF

To be filled in by the chair of the supervisory team.

chair

Zjenja Doubrovski

date

09 - 04 - 2021

signature

CHECK STUDY PROGRESS

To be filled in by the SSC E&SA (Shared Service Center, Education & Student Affairs), after approval of the project brief by the Chair. The study progress will be checked for a 2nd time just before the green light meeting.

Master electives no. of EC accumulated in total:

3

EC

Of which, taking the conditional requirements into account, can be part of the exam programme

-

EC

List of electives obtained before the third semester without approval of the BoE

YES

all 1st year master courses passed

NO

missing 1st year master courses are:

ID4170 Advanced Concept Design (21,0)

name

C. van der Bunt

date

16 - 04 - 2021

signature

C. van der Bunt

Digitally signed by C. van der Bunt
Date: 2021.04.16 14:13:18 +02'00'

FORMAL APPROVAL GRADUATION PROJECT

To be filled in by the Board of Examiners of IDE TU Delft. Please check the supervisory team and study the parts of the brief marked **. Next, please assess, (dis)approve and sign this Project Brief, by using the criteria below.

Does the project fit within the (MSc)-programme of the student (taking into account, if described, the activities done next to the obligatory MSc specific courses)?

Is the level of the project challenging enough for a MSc IDE graduating student?

Is the project expected to be doable within 100 working days/20 weeks ?

Does the composition of the supervisory team comply with the regulations and fit the assignment ?

Content:

☐ APPROVED

☒ NOT APPROVED

Procedure:

☒ APPROVED

☐ NOT APPROVED

- the missing course ACD should be finished before the green light meeting as agreed

comments

name

Monique von Morgen

date

28 - 04 - 2021

signature

IDE TU Delft - E&SA Department /// Graduation project brief & study overview /// 2018-01 v30

Initials & Name

D Tsoli

4922

Student number

5163528

Title of Project

Reversible Textile 3D Printing

IDE TU Delft - E&SA Department /// Graduation project brief & study overview /// 2018-01 v30

Page 2 of 7

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Reversible Textile 3D Printing

project title

Please state the title of your graduation project (above) and the start date and end date (below). Keep the title compact and simple. Do not use abbreviations. The remainder of this document allows you to define and clarify your graduation project.

start date 30 - 03 - 2021 end date 01 - 04 - 2022

INTRODUCTION **

Please describe, the context of your project, and address the main stakeholders (interests) within this context in a concise yet complete manner. Who are involved, what do they value and how do they currently operate within the given context? What are the main opportunities and limitations you are currently aware of (cultural- and social norms, resources (time, money,...), technology, ...).

Currently, there is a transition towards a future where the fashion system is circular. In this system, fashion items will be designed, sourced, produced and provided with the intention to be used and circulate responsibly and effectively in society for as long as possible in their most valuable form, and hereafter return safely to the biosphere when no longer of human use (Brismar 2014, 2017).

At the same time, there is plenty of research regarding products that combine 3D printed material with textile, both in fashion and architecture. Remarkable examples are the MIT Self-Assembly Lab, which experiments with innovative applications in fashion (Self-Assembly Lab, 2020), and Iris van Herpen Atelier, where the haute couture designer develops three-dimensional ethereal creations (Herpen, 2020). In the future, it is predicted that printing into textile will be a common practice in products.

But why is this material combination thriving? There are numerous advantages of the materials separately and together. Textiles are materials that designers know deeply and experiment often that vary in both form and application, have remarkable flexibility and soft nature. Nonetheless, forming a fabric is accomplished by labor-intensive actions that require skills and knowledge (Rivera et al., 2017). 3D printed materials offer a lightweight solution, provide support and create three-dimensional geometry frameworks for shaping other materials (Kycia, 2018), in this case the textile. From a sustainable point of view, 3D printing as a process has significant material savings, since its personalized nature produces no material waste (Lussenburg et al., 2003). Together, textiles and 3D printed materials, they create new possibilities for innovative design applications. However, in order to ensure a long life for the product, the two materials have to be reliably bonded and completely interlocked. Therefore, designers need to incorporate the fabric within the printed material (Doubrovski et al., 2017), which poses challenges for the end-of-life of the product, since they cannot be separated anymore.

In general, it is estimated that after the usage phase of garments, almost all the value in the materials they are made from is lost. Less than 1% of material used to produce clothing is recycled into new clothing (Shepherd et al., 2017). This can be attributed to the fact that the end-of-life of a product is highly dependent on the choices made during the development of a product (Rompa Group, 2020).

To conclude, 3D printing into textiles creates new design opportunities that bear the responsibility of integrating circularity in the final product application. This could be proved challenging if one takes into account the separation of interlocked materials and the contradiction between durability and recyclability.

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introduction (continued): space for images

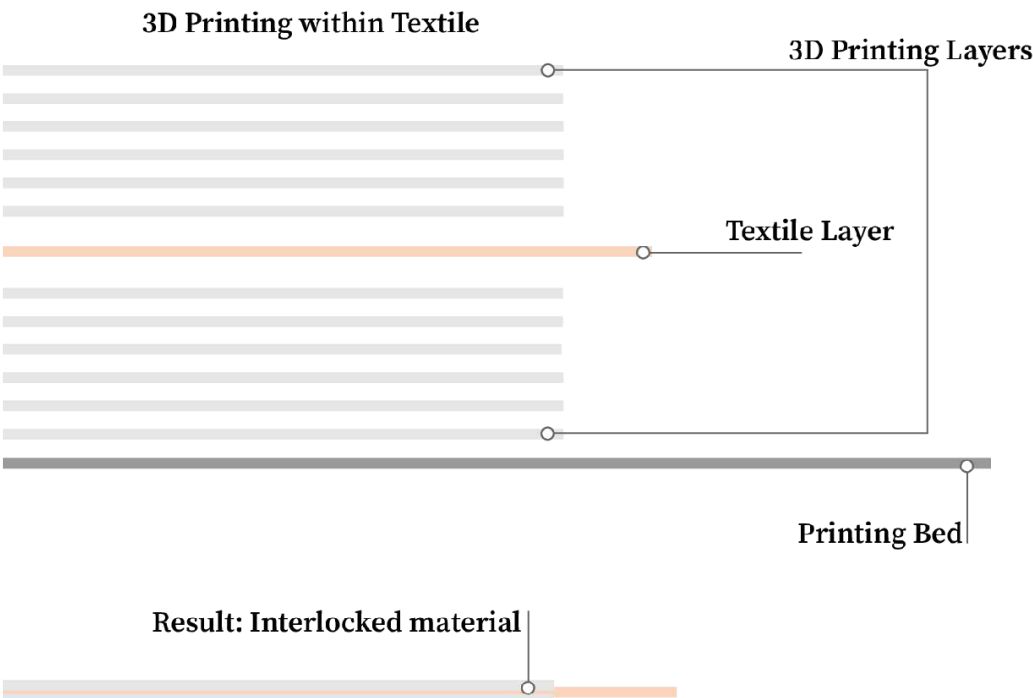


image / figure 1: Explanation of the 3D printing within textiles process.



image / figure 2: Ludi Naturae, the Foliage Dress, 3D printing within textile (Iris van Herpen, 2020).

PROBLEM DEFINITION **

Limit and define the scope and solution space of your project to one that is manageable within one Master Graduation Project of 30 EC (= 20 full time weeks or 100 working days) and clearly indicate what issue(s) should be addressed in this project.

The graduation project addresses the need to design for a future that is circular and innovative. Especially, it focuses on design for recycling and 3D printing into textile. Right now, there are problems when it comes to recycling of polymer reinforced textile. The material combination cannot be allocated to any of the recycling categories and separation of the materials is almost impossible to achieve or would require plenty of manual labor, which is not viable. The scope of this graduation project includes design for recycling, but it does not include recycling in the sense of using recycled material. Regarding the material, the exact textile and polymer are not defined yet, but the process is 3D printing within textiles, where textile is placed in-between layers of 3D print. Possibly, the textile will be a natural fiber and the polymer a recycled plastic. Finally, the exact application will be defined during the graduation project, but the product context will be within the boundaries of fashion.

With all that being said, the challenge is: How to design with 3D printing within textile in a way that is reliable and recyclable at the same time without compromising the functional and aesthetic value of the materials?

ASSIGNMENT **

State in 2 or 3 sentences what you are going to research, design, create and / or generate, that will solve (part of) the issue(s) pointed out in "problem definition". Then illustrate this assignment by indicating what kind of solution you expect and / or aim to deliver, for instance: a product, a product-service combination, a strategy illustrated through product or product-service combination ideas, In case of a Specialisation and/or Annotation, make sure the assignment reflects this/these.

The objectives of the graduation project are:

1. Develop a design method for 3D printing into textile that enables product circularity
2. Demonstrate the design with a product

The expectation for the project is to design a circular product by means of 3D printing into textile. Product circularity is characterized by minimum waste, durability and recyclability. Minimum waste is achieved by the usage of 3D printing and durability is ensured by the interlocking of the materials, but recyclability is currently not addressed. At this point it is important to mention that durability and recyclability are two characteristics that contradict each other, therefore it is a challenge to achieve both at the same time. For this reason, I will explore the possibilities of creating a connection -form variations, chemical combinations, mechanical properties- so that recycling is possible and disassembly requires a semi-automatic process instead of extensive manual labor. Regarding the second part, I will demonstrate this method by designing a product which will make use of the possibilities offered by 3D printing into textile and it will be intended for a textile application where three-dimensionality and lightweight structure are needed. Defining this application will also be also part of the exploration during this graduation project.

PLANNING AND APPROACH **

Include a Gantt Chart (replace the example below - more examples can be found in Manual 2) that shows the different phases of your project, deliverables you have in mind, meetings, and how you plan to spend your time. Please note that all activities should fit within the given net time of 30 EC = 20 full time weeks or 100 working days, and your planning should include a kick-off meeting, mid-term meeting, green light meeting and graduation ceremony. Illustrate your Gantt Chart by, for instance, explaining your approach, and please indicate periods of part-time activities and/or periods of not spending time on your graduation project, if any, for instance because of holidays or parallel activities.

start date 30 - 3 - 2021 1 - 4 - 2022 end date

		ACTIVITY PLANNING																																													
Calendar Week		13	14	15	16	19	20	21	22	23	24	25	26	27	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	1	2	3	4	6	7	8	9	10	11	12	13					
Available days for graduation per week		4	3	3	3	3	3	3	3	3	3	3	3	3	2	2	2	2	2	2	2	2	2	1	1	1	1	2	2	2	2	2	2	2	2	2	2	4	4	4	2						
Total Graduation Days		4	7	10	13	16	19	22	25	28	31	34	37	40	42	44	46	48	50	52	54	56	58	59	60	61	62	64	66	68	70	72	74	76	78	80	82	86	90	94	98	100					
Meetings		Kick-off														Midterm														Green Light Meeting										Graduation							
Deliverables		POC Vision														Provisional Design														Properties										Value				Showcase			
P H A S E S	Analysis – Research	Materials & 3D Printing Approaches/Methods																																													
		Recycling options for textile and plastic																																													
		Separation Approaches/Methods																																													
	Synthesis – Idea development	Potential Applications																																													
		Experimentation with rapid prototyping																																													
Ideation																																															
- A C T I V I T I E S	Simulation – Creation	Participation Session with experts																																													
		Decide on application and product																																													
		Modelling ideas and prototypes																																													
	Evaluation – Testing	Simulations focused on objective 1																																													
		Adaptation based on objective 2																																													
Testing simulations for objective 1																																															
Decision – Finalize	Testing with users for objective 2																																														
	Design evaluation based on criteria																																														
	Apply iterations																																														
Final Design Showcase																																															
Propose future iterations																																															

The graduation will be done part-time, starting with 3 days per week until the midterm evaluation, 1-2 days weekly until the green-light meeting, because of remaining obligations for the advanced concept design course, and full time for the rest. Despite the remaining course obligations, after contacting the board of examiners, I was allowed to start my graduation project.

The approach followed during the project is the basic design cycle (Boeijen et al, 2014). Starting with analysis, research will be conducted on materials, 3D printing and separation approaches and methodologies, recycling options for textile and plastic and potential applications. The deliverables from analysis will be the program of criteria, the design vision and the final application. Synthesis follows after that, where I will explore ideas through creative sessions, a participation workshop with either experts or end-users (depending on the findings from previous research and ideation) and experimentation through rapid prototyping. The outcome of this stage will be a provisional design. Next step will be simulation with outcome the expected properties, where the knowledge will be gathered by creating (research through design) and especially modeling ideas and prototypes, simulations focused on objective 1 and adaptation based on objective 2. Evaluation is a critical step in a design process. For this graduation project it will include laboratory testing for objective 1, user testing for objective 2 and of course evaluation of the design based on the criteria, resulting in the value of the design. Lastly, the decision phase of the project will finalize the design by applying iterations, designing the showcase, which will be a product and possibly a movie, and future iterations proposition. During this whole time iterations and repetitions are expected to happen and for this reason overlapping is calculated in the gantt chart. There will be updates every 6 working days and meetings with the supervisory team throughout the graduation with special attention to the formal meetings and their deliverables; kick-off meeting at the 30/03/2021, midterm evaluation at the 09/07/2021, green-light meeting at the 26/02/2022 and graduation ceremony at the 01/04/2022. In-between the graduation I will take 3 weeks of break, to rest and look towards the project afresh.

Personal Project Brief - IDE Master Graduation

MOTIVATION AND PERSONAL AMBITIONS

Explain why you set up this project, what competences you want to prove and learn. For example: acquired competences from your MSc programme, the elective semester, extra-curricular activities (etc.) and point out the competences you have yet developed. Optionally, describe which personal learning ambitions you explicitly want to address in this project, on top of the learning objectives of the Graduation Project, such as: in depth knowledge a on specific subject, broadening your competences or experimenting with a specific tool and/or methodology, Stick to no more than five ambitions.

The main driver for this project is my ambition to explore the boundaries of the fashion industry and attempt to contribute in a future fashion system that is circular and instead of condemning the environment, the fashion industry and designers use it as a source of inspiration to create products that celebrate its existence.

But why fashion? Because fashion products are used in daily life and by all people. Additionally, textiles have long tradition and a complex and fluid nature that can create extraordinary aesthetics and evoke emotions. However, it is time to fundamentally change their production, since it currently affects negatively their value and long-term prospects. Additive manufacturing is a promising production process that could create a positive impact if it gets further implemented into the industry, therefore it is worthy to research and design for.

Along the way, I intend to use my competencies from my studies so far. My mechanical engineering background will help me to deeper understand the material properties and 3D printing process. This understanding will be useful when researching the possible assembly processes as well as in testing the structures of the combined materials. A skill that I developed both in mechanical engineering and product design is 3D modelling, which will be crucial for the project in the iterative stage of design development during the 3D printing process. Moreover, during previous design projects I practiced design for disassembly which is highly relevant to the project, since it aims to achieve an outcome that allows both assembly and disassembly of the structure. At the same time, I aim to develop form, experience and aesthetics application on products, since it is an important aspect in fashion.

The competences I wish to acquire while working on the graduation project relate to rapid prototyping, textile in product design and circular design. Prototyping is a skill that allows designers develop and improve their products and especially rapid prototyping is increasing in popularity because of the creative freedom it provides to the designer. Textile is a very particular product category, therefore learning how to manipulate it will be a useful lesson, taking into consideration my motivation for the project. Finally, circular design is a big topic with a variety of applications. I plan to focus on learning how to design so that I create products with minimum waste, durability and recyclability.

This graduation project is deeply rooted in my personal learning ambitions and interests, which I have been contemplating before and during my studies. I believe that the objectives of the graduation project fall perfectly in line with the Integrated Product Design master, because I will be designing an integrated circular product for a sustainable future.

REFERENCES

- Boeijen, A. ., In Daalhuizen, J., In Zijlstra, J., In Schoor, R. ., & Technische Universiteit Delft. (2014). Delft design guide: Design methods.
- Doubrovski, Z., Stokhuijzen, D., Aberle, N., Herpen, I. van, Schuddeboom, P., & Verlinden, J. (2017). fabricating the Foliage Dress: Computational Design in Couture. *Fabricating the Foliage Dress: Computational Design in Couture*, 1281–1284.
- Herpen, I. van. About | Iris van Herpen. (2020). <https://www.irisvanherpen.com/about>
- Kycia, A. (2018). MATERIAL FORM-FINDING OF MODULAR TEXTILE STRUCTURES. *CA²RE PROCEEDINGS, Aarhus School of Architecture*, 53(9), 332–341.
- Lussenburg, K., Velden, N. Van Der, Doubrovski, Z., Geraedts, J., & Karana, E. (2003). Designing with 3D Printed Textiles. *Proceedings of the 5th International Conference on Additive Technologies*, 74–81.
- Rivera, M. L., Moukperian, M., Ashbrook, D., Mankoff, J., & Hudson, S. E. (2017). Stretching the bounds of 3D printing with embedded textiles. *Conference on Human Factors in Computing Systems - Proceedings, 2017-May(October)*, 497–508. <https://doi.org/10.1145/3025453.3025460>
- Rompa Group. (2020). The three phases of a product life cycle. [Rompagroup.com. https://www.rompagroup.com/news/the-three-phases-of-a-product-life-cycle.aspx](https://www.rompagroup.com/news/the-three-phases-of-a-product-life-cycle.aspx)
- Self-Assembly Lab. (2020). Self-Assembly Lab. Self-Assembly Lab. <https://selfassemblylab.mit.edu/>
- Shepherd, J., Brodin, H., Cave, C., Waugh, N., Price, A., & Gabbay, J. (2017). a New Textiles Economy: Redesigning Fashion’S Future. *Ellen Macarthur Foundation*, 150. https://www.ellenmacarthurfoundation.org/publications/A-New-Textiles-Economy_Full-Report_Updated_1-12-17.pdf%0Ahttps://www.ellenmacarthurfoundation.org/assets/downloads/publications/A-New-Textiles-Economy_Full-Report_Updated_1-12-17.pdf

FINAL COMMENTS

In case your project brief needs final comments, please add any information you think is relevant.

The following page includes the references for this document.

