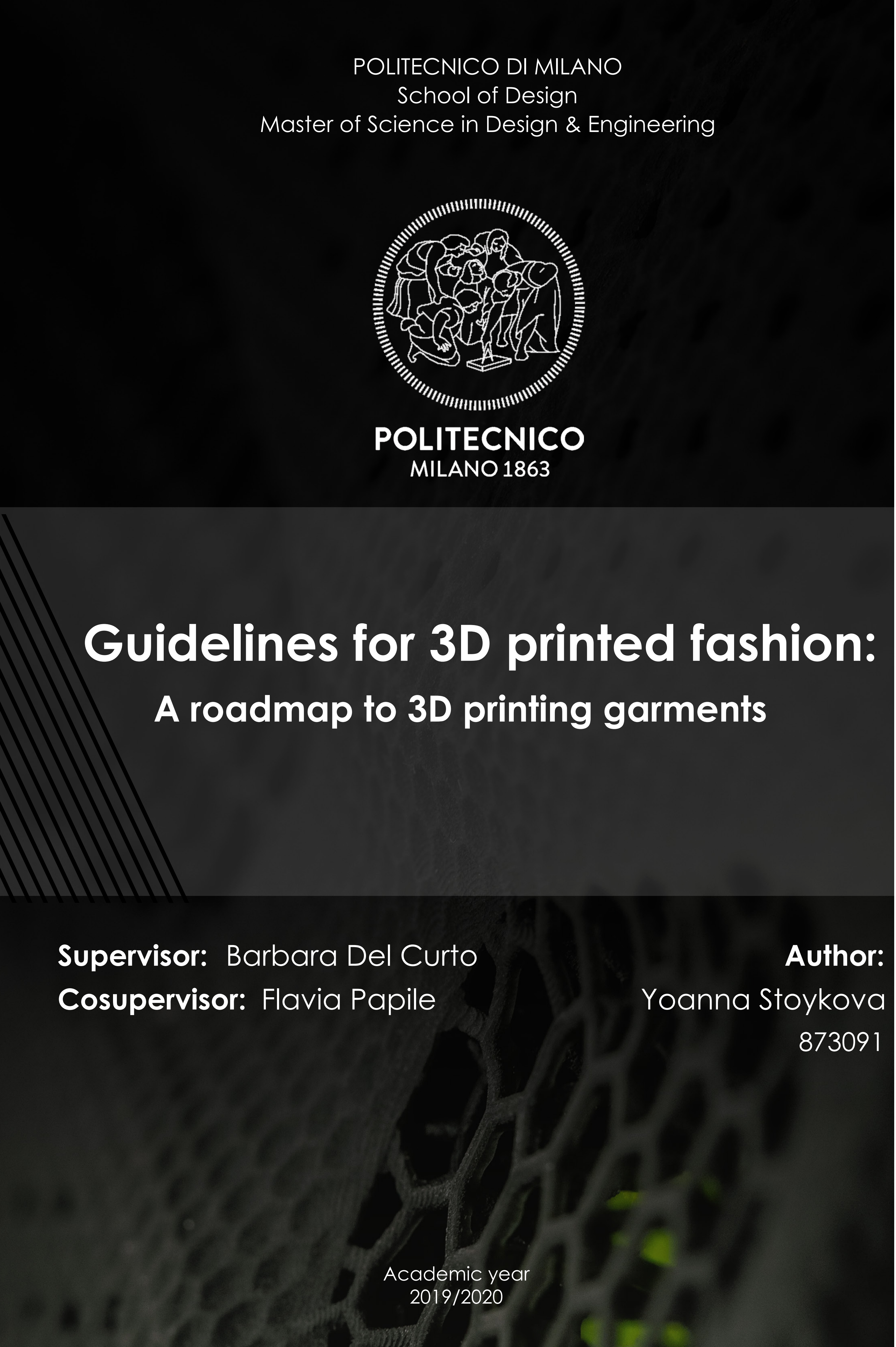

POLITECNICO DI MILANO
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Guidelines for 3D printed fashion:

A roadmap to 3D printing garments

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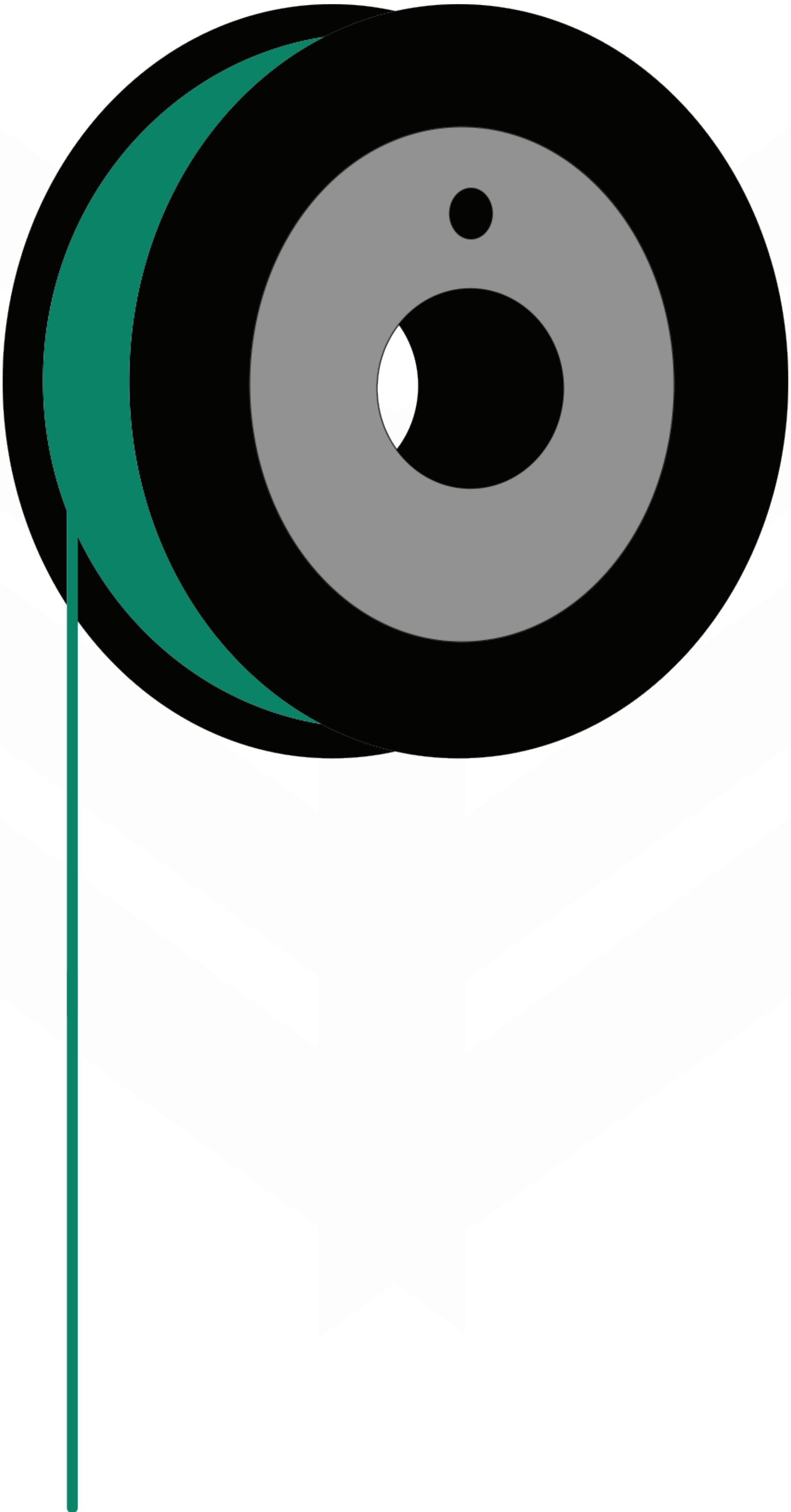

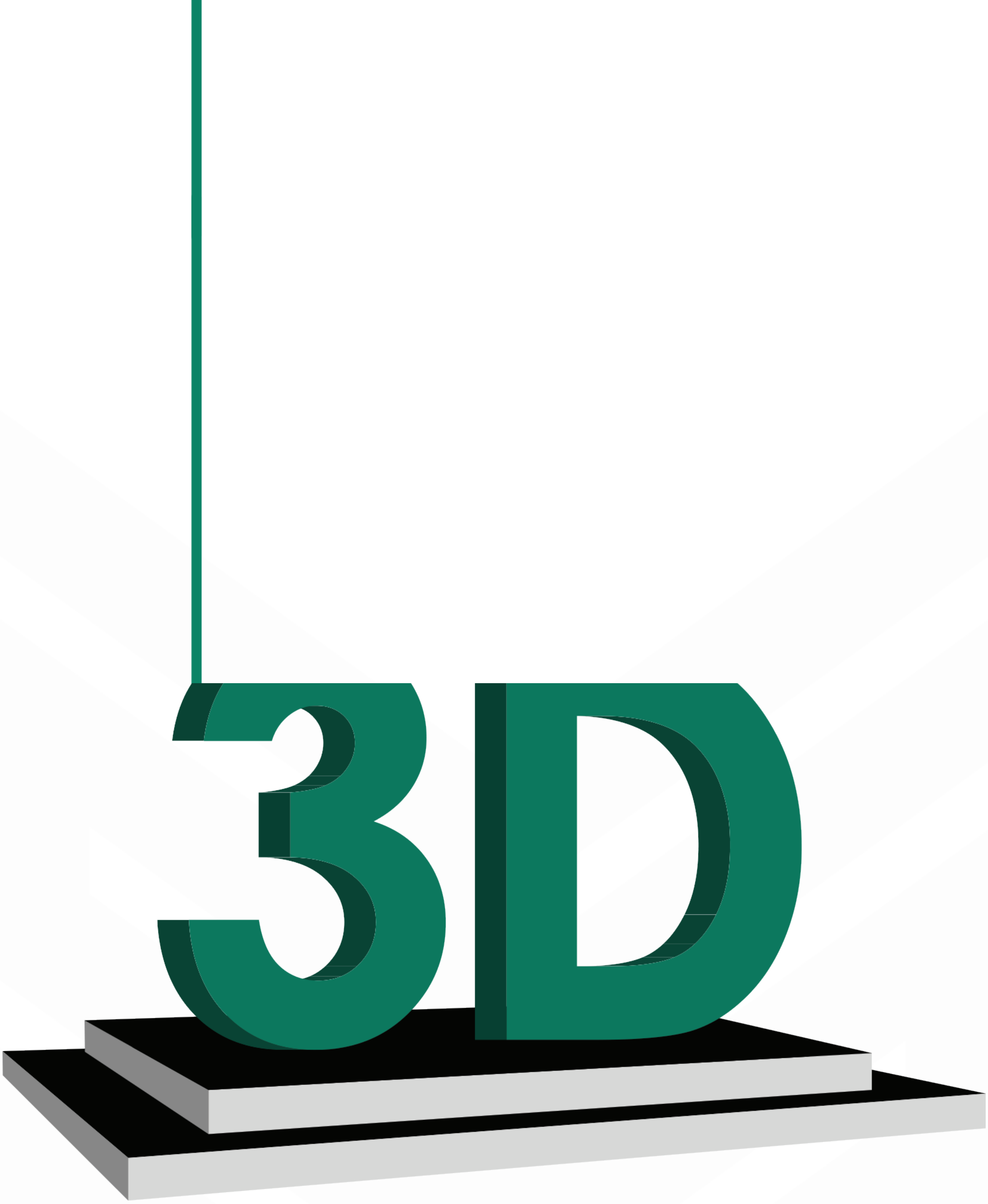

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ABSTRACT

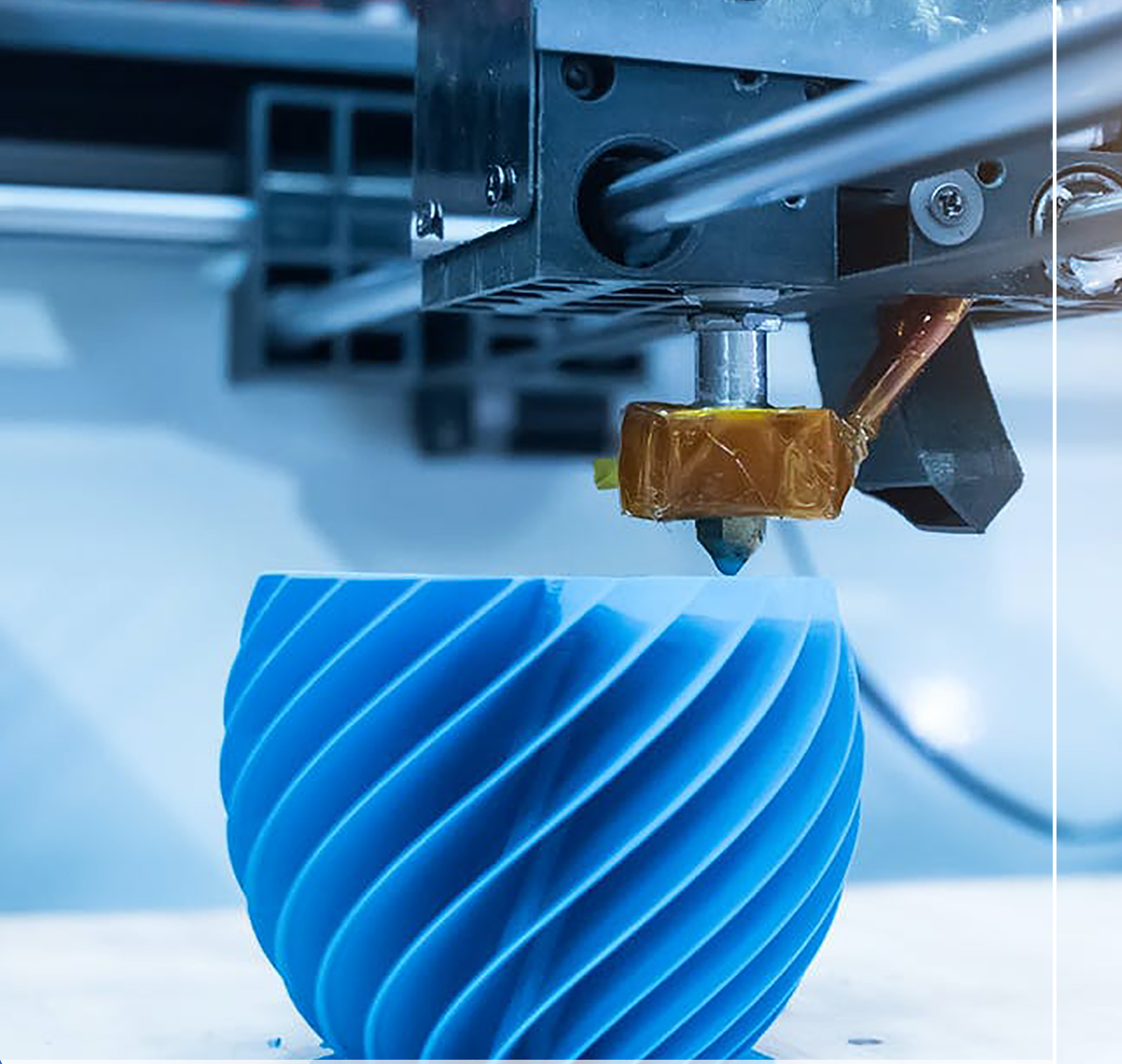
L’utilizzo della stampa 3D è in aumento anche nel mondo dell’industria tessile e della moda, grazie ai suoi campi applicativi e potenziale in espansione in molti settori. A causa delle tendenze nel campo della moda, da sempre in continuo cambiamento, e molte richieste di prodotti personalizzati per alcuni segmenti della clientela, la ricerca sulla produzione di tessuti stampati in 3D assume oggi un ruolo fondamentale. I tessuti stampati in 3D hanno proprietà fisiche e chimiche diverse a seconda di differenti tecnologie e materiali di stampa. Tuttavia è difficile produrre tessuti stampati in 3D che soddisfino i requisiti come flessibilità, drappeggio e comfort necessari per l’implementazione nel mondo della moda. L’obiettivo di questa tesi è fornire una guida completa utile ai designer su come stampare i tessuti in 3D. Nel primo capitolo vengono introdotti i concetti fondamentali dei processi di produzione additiva. Quindi viene realizzata una breve panoramica dei metodi di produzione tessile tradizionale, dei materiali e delle proprietà richieste, importante per fornire ai designer le conoscenze di base su come vengono realizzati i tessuti. Nel terzo capitolo, sulla base di ricerche su altre pubblicazioni e di un benchmark su indumenti stampati in 3D già esistenti, verrà effettuata una classificazione dei tessuti in termini di struttura e materiali. Ciò contribuirà ad analizzare i materiali e le tecnologie adatti per ottenere importanti proprietà come flessibilità e drappeggio. Successivamente, verranno presentati case studies di tecniche interessanti nella stampa 3D. In base a tutti questi contenuti, il capitolo finale fornirà informazioni e regole di progettazione specifiche da utilizzare durante stampa, e una tabella di marcia con tutti i passaggi che devono essere seguiti durante la progettazione di indumenti stampati in 3D. La conclusione finale chiarisce le implicazioni industriali della stampa 3D e alcuni suggerimenti di ricerca per il futuro.

Parole chiave: produzione additiva, stampa 3D, tessuto stampato in 3D, indumento, fibra, linee guida

The use of 3D printing is also increasing in the textile and fashion industry as its application and potential accelerates in diverse industries. Since the fashion trend is rapidly changing and there are high demands of customized products for customer segments, research on manufacturing of 3D printed textiles has become more important. 3D printed textiles have different physical and chemical properties depending on a variety of 3D printing technologies or materials. However, it is difficult to fabricate 3D printed textiles that meet demand for garments such as flexibility, drapability, comfort so that it can be implemented in the fashion industry.

The aim of this thesis is to provide a complete guide for designers of how to 3D print garments. In the first chapter the fundamentals of additive manufacturing processes are introduced. Then a brief overview of the traditional textile production methods, materials and required properties is made, which is important for the designers and give them the basic knowledge how textiles are made. In the third chapter , based on a literature review and benchmark on already designed 3D printed garments, a classification of printed textiles will be made in terms of structure and materials. This will contribute to analyze the suitable materials and technologies for achieving important properties like flexibility and drape. Afterwards, study cases of interesting techniques in 3D printing will be presented. Based on this review the final chapter will provide information for specific design rules when 3D printing and a roadmap with all the steps that must be followed when designing 3D printed garments. A final conclusion reveals the industrial implications of 3D printing and some future research suggestions.

Key words: Additive manufacturing, 3D printing, 3D printed textile, garment, fiber, guidelines



CHAPTER I.

ADDITIVE MANUFACTURING: AN OVERVIEW

1.1 INTRODUCTION

Additive manufacturing (AM), known as threedimensional 3D printing or rapid prototyping (RP), is a series of various processes and technologies in which material is added or solidified under computer control to create a three-dimensional object, using digital data from a 3D model (Tosoni, R., 2019). The technology was developed in early 1986 by Charles Hull, the inventor of the solid imaging process known as stereolithography (SLA), and Scott Crump, inventor of fused deposition modeling (FDM). Subsequent developments were such as powder bed fusion, inkjet printing, and contour crafting (CC) (Tuan D. Ngo, 2018).

Nowadays it is a unique technology that can produce any kind of three dimensional object with great precision and is thereby it is widely applied in different industries like construction, biomechanics, and prototyping (Figure 1.1). A wide range of materials is used including metals, polymers, ceramics, and concrete.

Figure 1.1. Complex 3D object
Image source: www.amfg.ai

Although 3D printing is a recent technology it has been used in various industries from models to items. One of the challenges which producers are facing is the product customisation due to the high costs of creating custom-tailored items for end-users.

The growing consensus of adapting the 3D manufacturing system over traditional techniques is attributed to several advantages including fabrication of complex geometry with high precision, maximum material savings, flexibility in design, and personal customisation (Tuan D. Ngo, 2018).

This chapter will provide a comprehensive review of 3D printing techniques, advantages, and disadvantages, opportunities, and state-of-the-art.

1.2 WHAT IS ADDITIVE MANUFACTURING?

Additive manufacturing (AM), rapid manufacturing, or 3D printing is the collective term for all processes and techniques for the fabrication of complex geometries and structures (Tuan D. Ngo, 2018). The term rapid prototyping refers to a rapid process that creates something quickly which ends up in a prototype or a final product (Figure 1.2).

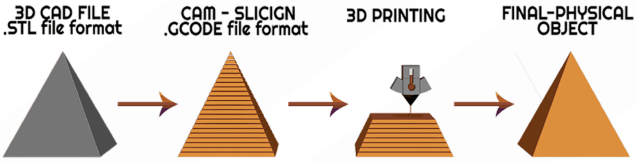


Figure 1.2. How 3D Printing Works in 4 steps
Image source: www.my3dconcepts.com

The main principle on which AM is based, although it sounds simple, is that a three-dimensional computer-aided design (CAD) model is sliced in discrete layers (Figure 2). In this way, the process of producing complex 3D objects is simplified. Compared to other manufacturing processes AM does not need any additional analysis of the geometry of the part or which tools should be used. Some basic dimensional details as long as understanding the working principles of the AM machine is sufficient.

The nature of AM processes can be described in terms of adding material in layers (layer processing). Each layer can be defined as a thin cross-section of the part and must have a finite thickness. The more layers, the more accurate will the final part be. This means that to have higher precision, layers need to have an adequate thickness. What all AM processes have in common is that they produce a 3D object through adding material - layer-based.

The differences are in the materials that are used and in the way layers are added and bonded (Gibson I., 2015). All commercialized AM machines to date use a layer-based approach, and the major ways that they differ are in the materials that can be used, how the layers are created, and how the layers are bonded to each other.

Additive manufacturing processes include several steps from CAD data to the final part depending on the complexity of the desired product. For some, it might require additional post-processing steps while for other more simple parts it can only use AM for visualization models.

In most cases the following steps are involved:

Step 1: CAD
A software model that fully describes the external geometry. Almost any CAD solid modeling software can be used.

Step 2: Conversion to STL
Every AM machine works with STL files. It is directly converted from the CAD software to realize the slicing of the geometry.

Step 3: Transfer to AM Machine and STL File Manipulation
The STL file is transferred to the machine and it can be adjusted in terms of position, orientation, etc.

Step 4: Machine Setup
Here can be adjusted the parameters of the machine such as filament, energy, source, layers, thickness.

Step 5: Build
It's an automatic process that carries out the building of the part. It may require some monitoring if there are any errors or it is running out of filament.

Step 6: Removal
The part is completed and can be removed.

Step 7: Post-processing
Parts may require some post-processing like support removal.

The nature of AM processes can be described in terms of layer processing. Material within a layer can be processed sequentially, where the shape of the layer is formed by a laser (Figure 1.3). This is 0D (although in reality, the spot does have a surface area), in which the laser needs to scan in both an X- and Y-direction to cover the entire layer area (Hopkinson and Dickens, 2006).

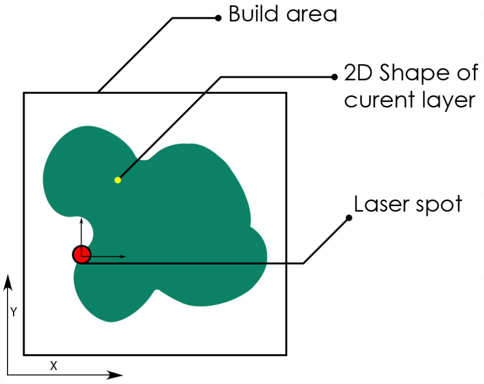


Figure 1.3. 0D proccessing

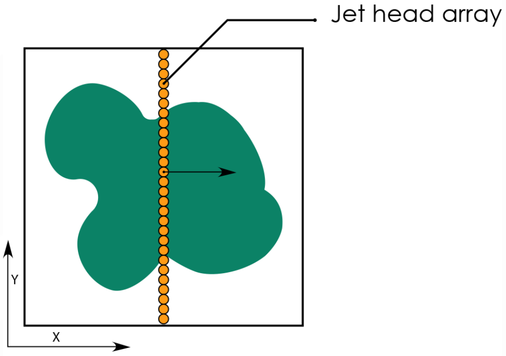


Figure 1.4. 1D proccessing

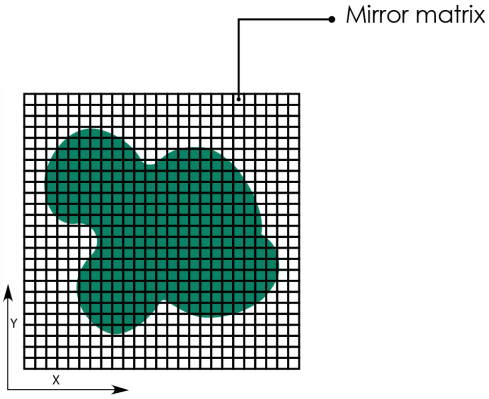


Figure 1.5. 1D proccessing

Layer processing can also happen simultaneously in arrays or matrices (Figure 1.4). In case of arrays, this is termed 1D, in which the array is in one dimension (Y) and the printhead only needs to move in one direction (X) to form a complete layer. The term 2D is used for matrices, in which a two-dimensional matrix covers an entire area, without the need to scan or move (Hopkinson and Dickens, 2006), as shown in Figure 1.5.

1.3 COMMON ADDITIVE MANUFACTURING PROCESSES

Most common for all AM processes is that are layer-based as mentioned above. This means the material is being added rather than subtracting material as in traditional manufacturing processes. The difference between the processes lies in the manner in which material is added. They can be classified by seven standardized terms, used to describe the different nature of the processes (Tuan D. Ngo, 2018).

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

1.3.1. Stereolithography

Stereolithography is a vat photopolymerization process (Figure 1.6). An ultraviolet laser is used to cure a liquid photopolymer layer by layer. The laser is driven by a CAD-file, which cures a selected part of the polymer onto a platform. The platform is lowered in tiny steps (typically around 100 µm), allowing a new layer of liquid polymer to flow over the previous layer, which can then be cured by the laser (Hopkinson and Dickens, 2006). SLA is an example of a 0D-processing.

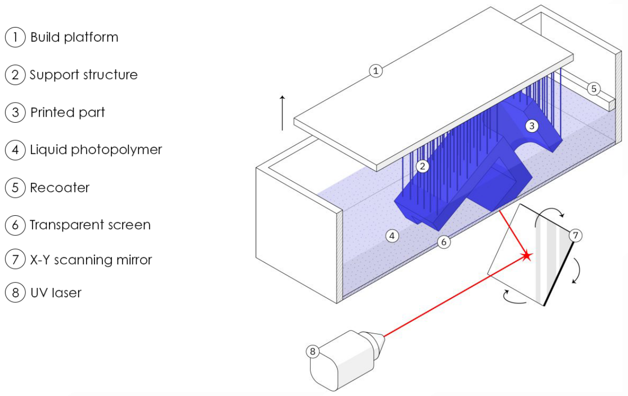


Figure 1.6. Stereolithography (SLA)
Image source: www.3dhubs.com

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

1.3.2 Selective laser sintering

This is a powder-based process similar to SLA (Figure 1.7). Instead of a liquid polymer, a powdered material is used. The powder on top of the powder bed is sintered, after which a new layer of powder is added by rollers to the top. In this way, the laser builds the product out of two-dimensional layers by means of 0D-processing. The powder that is not fused by the laser acts as a support material, which can be removed using compressed air, and afterwards partly reused. To reduce thermal gradients and energy required for the laser, the powder is preheated to a lower temperature. [Hopkinson and Dickens, 2006]

However, this also partially degrades the powder, which is why approximately 10-40% of the powder ends up as waste (Telenko, 2010).

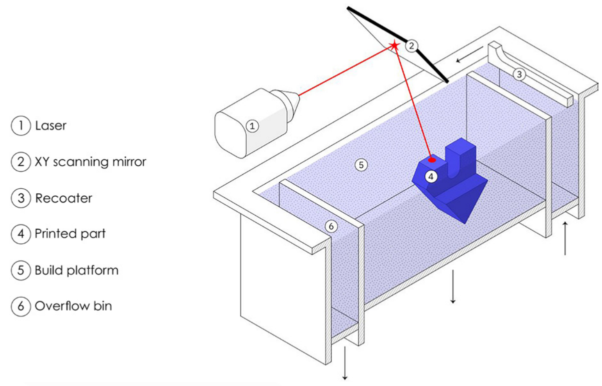


Figure 1.7. Selective laser sintering (SLS)
Image source: www.3dhubs.com

Advantages of SLS: stable parts, good mechanical properties, and a large variety of materials that can be used.

1.3.3 Fused deposition modelling

The term Fused Deposition Modelling was first commercialized and patend by Stratasys. In response, other companies adopted the term Fused Filament Fabrication (FFF), in order to be used legally unconstrained (RepRap,2014). Both terms refer to the same solid-based process, in which the material is extruded trough a nozzle, as shown in Figure 1.8.

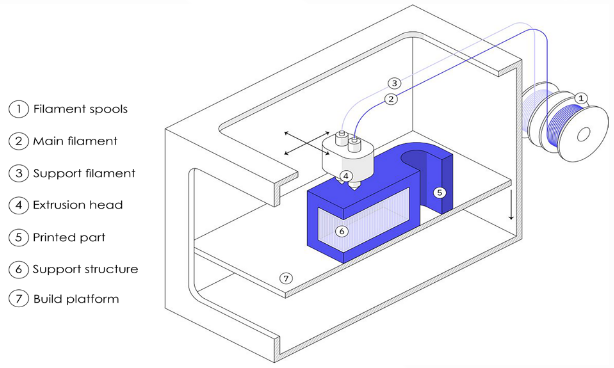


Figure 1.8. Fused deposition modelling
Image source: www.3dhubs.com

The nozzle extrudes and deposits material layer by layer. The resolution of the part is limited by the diameter of the nozzle (typically around 0,3mm) (Hopkinson and Dickens, 2006). Due to the nature of the process, creating overh--anging parts is limited without the use of a support structure, which later has to be removed. The process is easy to set-up and has become the most popular choice for home use.

1.3.4 Polyjet technology

In PolyJet technology, the deposition of material is simultaneous using an array of printing heads (1D processing). The material is an acrylate-based photopolymer, which is hardened using a UV-lamp.The accuracy of the layers can be up to 16 µm (Hopkinson and Dickens, 2006). Supports are added automatically. They can be removed later on with a water jet (Figure 1.9). The latest innovation in PolyJet technology is the ability to print using multiple materials at once, for instance, a hard material can be mixed with a flexible material within the same part.

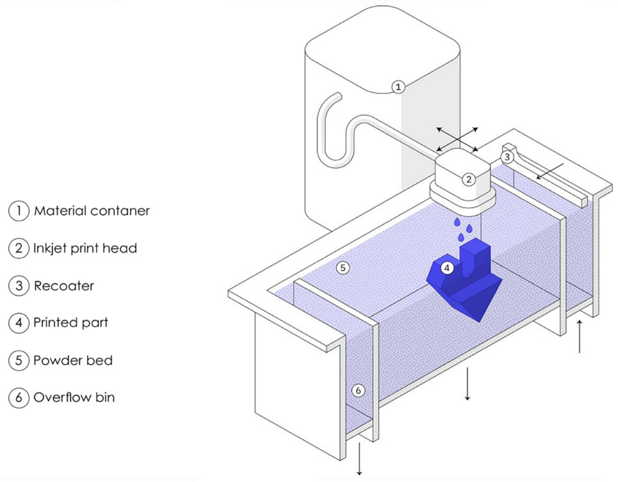


Figure 1.9. Polyjet technology
Image source: www.3dhubs.com

The latest innovation in PolyJet technology is the ability to print using multiple materials at once, for instance, a hard material can be mixed with a flexible material within the same part.Besides the possibility of printing multiple materials, PolyJet technology offers a high resolution, the ability to print complex parts, and no post-processing, except forthe removal of the support material. However, the technology requires expensive equipment and is not suitable for home usage.

1.4 PROS AND CONS OF AM

Additive Manufacturing, unlike the traditional manufacturing processes (for instance Figure 1.10), gives the possibility for mass customization of products. Nevertheless it enhances the production times of small products in high quantities. However some drawbacks must be pointed out.

Figure 1.10. Comparison between AM and Subtractive manufacturing
Image source: www.innopowder.innomaq21.com

Main advantages of AM are (ACMA Staff, 2014):

- Fast design development with the possibility for complex shapes without the need of a mould or any tools. Designing for AM could result in different mechanical properties in different areas of the part.
- Cost-effective, convenient, and less scrap material
- Wide range of materials from metals to ceramic, especially plastics and bi-materials.
- Flexible process which means it can be easily adapted if changes occur. It will not require any other investments like traditional manufacturing.
- Rapid prototyping is important regarding time. Due to this the product can be tested immediately.
- It doesn't require special training and skills to use the machines. Of course, it is important to mention that the designing process requires knowledge in designing for manufacturing.

On the contrary, the main disadvantages are:

- One of the problems is that the printer is relatively slow and the building process demands some time.
- Often the finish is rough and needs post-processing like smoothing the surface, removing the supports, painting. It is related with the two most important parameters: resolution and layer thickness. They impact the product's uniformity.
- The process is not subject for automatization because it is discontinuous and parts can be produced one by one.
- Comfort and flexibility that 3D printed only parts are expected to provide. The most current materials do not absorb moisture at all. For several cases,probably unexpected for some people, but the real problem is the price, based on the low productivity.
- Products are limited in size which means for larger ones a larger printer will be needed.
- It is still considered an expensive investment. It can vary from 5000euro - 50000euro for a relatively good one.

1.5 OPPORTUNITIES AND STATE-OF-THE-ART BOUNDARIES

In this section some of the opportunities that additive manufacturing can provide for many sectors and future developments, will be reviewed (Table 1.1)

1.5.1 Opportunities

Additive manufacturing provides a number of opportunities regarding garment design: shape complexity, material complexity hierarchical complexity and functional complexity.

A reduction of assemblies is beneficial not only for cost reasons, but also because no compromises have to be done for manufacturing and assembly reasons (Hague, 2006).

Another benefit of shape complexity is the reduction of process steps. The entire product development process is sped up by the use of computers (Gibson, Rosen and Stucker, 2015). Usually additive manufacturing production processes are performed in a single step, although often finishing processes are required.

OPPORTUNITES

SHAPE COMPLEXITY	Design optimisation Part consolidation Customization Multiple assemblies Reduction in process steps
MATERIAL COMPLEXITY	Heterogeneous materials Property gradients
HIERARCHICAL COMPLEXITY	Ministructure Macrostructure Mesostructure
FUNCTIONAL COMPLEXITY	Functional devices Pre-assemblied parts

Table 1.1. Opportunities of AM

Complexity in shape allows the creation of multiple assemblies in one production process.

Material complexity

Traditional manufacturing techniques often limit the functionality to the properties of one homogeneous material. Additive manufacturing has given rise to the opportunity to deposit multiple materials in any location or combination necessary. It is known as *functionally graded materials (FGM)* (Hague, 2006). Although this is not yet fully optimised, it is becoming a more viable concept by development of multi-material 3D printers.

Not only the use of heterogeneous materials, but also the chance to create different material properties is a great potential. The nature of many AM processes enables changing thematerial composition in gradients or abruptly (Gibson, Rosen and Stucker, 2015).

Hierarchical complexity

Hierarchical complexity includes the micro-, meso- and macrostructure of a part. All of them can be controlled and designed in order to obtain desired properties. The idea behind this is that every feature can have a smaller feature added to it, and all of these smaller features can also have smaller features added to them etc. (Gibson, Rosen and Stucker, 2015).

This can be expressed in three examples: tailored microstructures, textured surfaces and cellular materials (materials that are designed to have material only where it is needed, which results in light, stiff and strong materials (Gibson, Rosen and Stucker, 2015).

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

Functional complexity

Due to the nature of additive manufacturing processes, it is always possible to have access to the inside of the part. This makes it capable to fabricate operational mechanisms during the process, or to insert prefabricated assemblies [Gibson, Rosen and Stucker, 2015]. This provides opportunities especially for smart textiles and wearables.

1.5.2 State-of-the-art

As said over, 3D printing appears to be advantageous for clothing generation. In any case, it hasn't been broadly connected yet.There are a few restrictions with respect to the state-of-the-art and so is the usage of this kind of technology (Table 1.2).

One of the restrictions happens to be within the CAD demonstrating frameworks. In spite of the fact that parts are made of numerous little components, most commercial CAD frameworks cannot perform calculations with more than 1000-2000 components (Gibson, Rosen and Stucker, 2015).

Displaying complex 3D structures is in this manner troublesome and time-consuming. Another challenge is displaying a textile like structure that's bended and adaptable as the shape of a human body. Current CAD frameworks are not planned to execute these sorts of calculations. Subsequently, the potential of additive fabricating for numerous congregations lies within the hands of the advancement of CAD systems.

STATE OF THE ART BOUNDERIES

PROCESS LIMITATIONS	CAD Systems Support structures Process time
PRODUCT LIMITATIONS	Available materials Resolution Size
HUMAN LIMITATIONS	2D Thinking

Table 1.2. State-of-the-art of AM

Another impediment appears to be the bolster structures in overhanging structures and complex congregations. Depending on the geometry and handle, it may well be essential to include back structures within the model which need to be expelled at the conclusion.

For complex geometries, this is often a dull and time-consuming handle, and the portion may well be harmed. In this sense, AM materials - complex numerous congregations with a parcel of little joins, are most likely to encounter harm whereas evacuating the underpins. In other words it might be inconceivable. There's an arrangement of course - dissolvable materials can be utilized for bolster structures but the truth that they are not naturally neighborly, ought to be considered as well.

Handle time is additionally a restriction. 3D printing takes hours in the event that it comes to expansive and complex parts. It depends on the sort of process,the build-density of the and the volume of the support (Telenko, 2010). Be that as it may, this may be put in viewpoint by the reality that added substance fabricating diminishes the entire handle time by minimizing the number of steps (as discussed over). The size of the item that can be created is subordinate on the size that's accessible within the 3D printer. On the off chance that the portion is as well expansive to fit within the printer, it can be cut into a few smaller parts and amassed afterward. In spite of the fact that most printers are still restricted in measure, advancements are ongoing. The following genuine restriction is the materials. For most forms, there are a number of plastics accessible, as well as metals and ceramics. Other sorts of materials are in advancement, but as of now most inquire about centers on materials that can be softened in order to be utilized within the current printing processes.

The key to making printed materials that have comparative properties as materials, is imitating their little structure. In order to form these small structures, the printing resolution ought to be increased.

Within the long term, it would be useful in the event that the whole preparation of 3D-modelling may well be rearranged, or more advanced for the particular necessities for garment design.

1.6 CONCLUSIONS

3D printing gives a parcel of benefits for the generation of articles of clothing. 3D printing makes it conceivable to form personalized pieces of clothing, in essentially any shape, and diminishes the number of generation steps. It moreover permits localized contrasts in fabric and structure, optimized for changes in usefulness inside one item.

On the other hand, the technology still needs to develop further before this can become reality. Progresses in CAD frameworks, in printing innovation and, most critically, within the way we think of and plan pieces of clothing are essential in arrange to 3D print utilitarian pieces of clothing: we still tend to think approximately items by the confinements forced by Plan for Fabricating and Gathering, rather than thinking in a way permitted by the conceivable outcomes of 3D printing.

In this chapter has also appeared that there are a number of distinctive printing forms. There's no perfect preparation; the choice ought to depend on the required plan and properties.

Although in hypothesis it is possible to make whole 3D articles of clothing in one prepare, there's a information crevice that anticipates it from being as often as possible utilized in home. Mold originators are commonly the fashion designers, however they are not prepared to work with 3D modelling programs. Their instruction centers on considering in 2D designs, instead of 3D items. In this manner, it is recommended to get them familiar with added substance manufacturing by printing 2D design pieces (Mikkonen J., 2013).

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

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CHAPTER II.

GARMENTS AND TEXTILES

2.1 INTRODUCTION

Usually textile products are described using the material of the fiber e.g. cotton shirt, wool scarf and nylon parka. It is important to distinguish fabric and textile and what their performances are. Fibers are fundamental in the production of fabrics and have been used for years until 1885 when the first fiber was manufactured. Before that the strands were absolutely natural, derived from plants. Later on many more were invented.

In current years, excessive research has taken place in the development of new fibers and methods of textiles fabrication. The new modern fibers are used now in nanotechnology, smart, technical, multifunctional and high performance applications.

In order to design a meaningful product, it is useful to look at the properties that should exist in the finished product. In the following chapter textiles will be reviewed in terms of structure, fabrication, properties and function.

2.2. STRUCTURE OF GARMENTS

Traditional textiles are flexible materials created by interlocking fibers/yarns. They have functions, as a garment, such as isolation and protection of human bodies from the environment. Although these generic functions, now their role has changed in a more aesthetic way. They are used for self-expression, personalization or even represent social status (Fletcher, 2000).

However, examining garments more closely seems that they can be structured in different levels with their unique characteristics. Starting from the top component (the garment) up to the smallest (the fiber), it can be stated that fibers are used for the creation of the yarn, then the yarn is knitted or woven into textile. After which, using different techniques, the textiles are assembled in a garment.

The structures applied in garments are important in order to create a well-fitting piece of clothing and they will be reviewed in the following sections in means of production of textiles.

The definitions of fiber, yarn and garment will be given in the following sections along with the manufacturing techniques.

2.3. YARNS

The term yarn can be defined as a linear collection of filaments or fibers in a twisted state or bound by other means, and possessing good tensile strength and elasticity properties (Das. A, 2015). From the various types of commercially manufactured yarns, it may be seen that there is a great number of functional and design possibilities. Fibers are processed in both pure and blended states.

Yarns are produced by means of spinning that consists of three consecutive steps. The first step is drafting of the fibers, in which the fibers from the input strand are aligned along the axis of the yarn in the appropriate density. The second step is binding the fibers together, by providing enough cohesion so they form a uniform thread. This can be accomplished by twisting, entangling, wrapping or bonding the fibers. The last step is wrapping the yarn around a bobbinor some other type of packaging.

Yarns can be categorised according to the type of fiber in three basic types: (Figure 2.1)

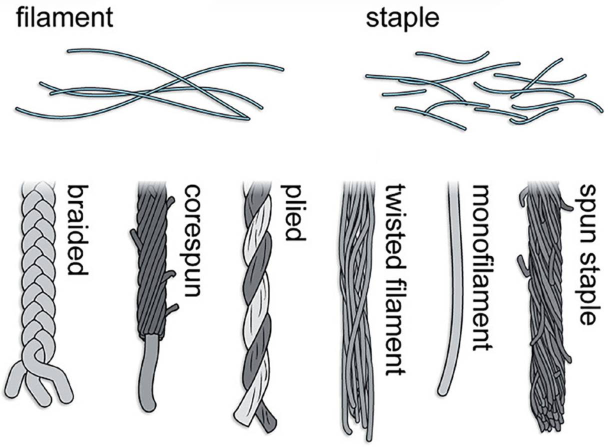


Figure 2.1. Types of yarn
Source: www.onlinelibrary.wiley.com

- Monofilament - yarns with only one filament
- Multifilament - many filaments are twisted together to form multifilament yarns
- Staple or spun - staple yarns are defined as assembled strands of fibres twisted together to form a continuous strand according to the properties required (Table 2.1)

In general, staple fibers are made into a yarn through drawing, spinning and twisting. This allows an assembly of fibres to hold together in a continuous strand. There are different methods of spinning, depending on the fiber being spun which will not be discussed in detail.

The basic spinning process involves three steps as it follows. The first step is to draft the fibers in the appropriate density, aligning them with the axis of the yarn. A typical yarn will contain approximately 100 fibers in the cross-section (Lewin, 2007). The second step is binding the fibers together, by providing enough cohesion so they form a uniform thread. This can be accomplished by twisting, entangling, wrapping or bonding the fibers. The last step is wrapping the yarn around a bobbin or some other type of packaging.

The type of spinning process depends on the characteristics of the input fibers and the desired properties of the yarn. Therefore a classification based on their physical and performance properties has been made (Das. A, 2015). The combination of different fibers and yarn structures can be used to engineer a particular set of properties. Sewing threads are an example of a yarn that is specifically engineered for a specific purpose (Das. A, 2015).

2.4. FIBERS

Fibers are long, thin and flexible materials that are the foundation for all textile products. They can be divided into two categories: natural and man-made (Table 4). Natural fibers can be divided into vegetal, animal and mineral fibers. Their main components are either cellulose or protein (Duquesne, 2007). Man-made fibers can be synthetic or regenerated.

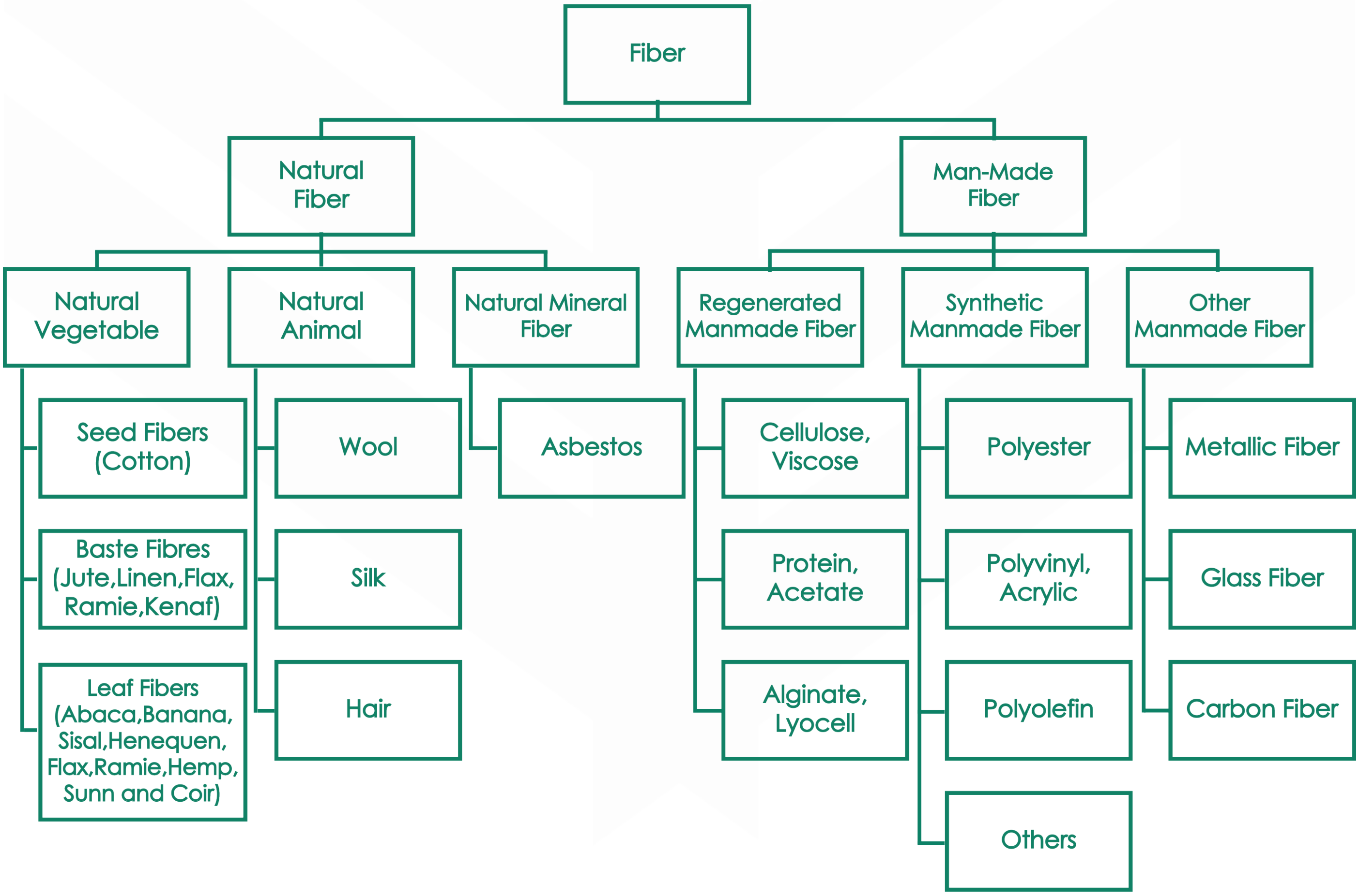


Table 2.1. Classification of fibers

2.4.1. Natural fibers

Natural fibers account for roughly 45% of the whole fiber generation. These filaments have common traits that make them desirable for clothing applications. They are frequently favored over engineered strands, either for status, comfort, or strength reasons. All natural fibers are staple strands (filaments of limited length), except for silk, which is continuous.

Vegetal fibers

The main component inl vegetal fibers is cellulose (Goswami, 2004). Cellulose is one amongst the most building elements of all natural materials, and is an inexhaustible, renewable material. It exists within the sort of fibers in wood, cotton and other plants and is the commonest organic polymer. Cotton consists of quite 90% cellulose, while the cellulose content of wood is around 40-50%. The form and structure of cellulose fibers are answerable for the properties that make it desirable for textiles (Figure 2.2).

Animal fibers

The source for these strands is either animal hair or silk. The basic component of animal fibers is protein (Duqesne, 2007). Silk is the only continuous natural fiber. Its main component is fibroin, a protein, which forms the structural part of the silk.

Figure 2.2. Examples of animal and vegetable fibers
Source: www. goodmenproject.com

Mineral fibers

The only naturally occurring mineral fibers are asbestos, a collective term for a group of six different mineral fibers. Although they have many desirable properties, such as fire resistance, flexibility and high tensile strength, their renowned health risks have caused a rapid decline in usage (Figure 2.3).

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

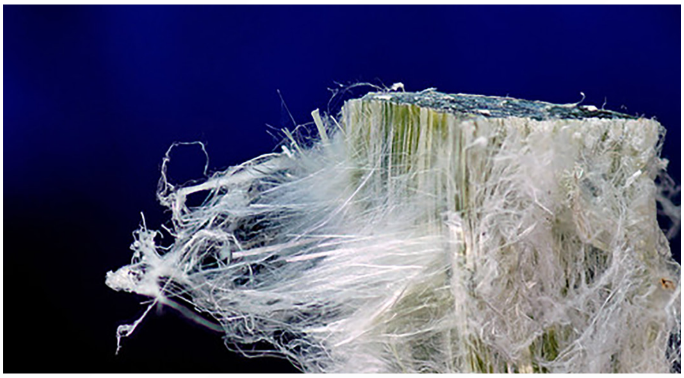


Figure 2.3. Mineral fiber
Source: www.flickriver.com

2.4.2. Man-made fibers

Regenerated and synthetic fibers are known as man-made or manufactured fibers. Although man-made fibers often aim to copy the properties of their natural counterparts, they can also offer a variety of properties that are not available in natural fibers (Figure 2.4).

Man-made fibers are generally continuous fibers, although they are often subjected to a number of processes to transform them into staple fibers. In theory, man-made fibers can be produced with any cross-section.

Manufactured, or man-made, fibers can be classified as:

- Synthetic polymers, e.g. polyester, nylon (polyamide), acrylic, lycra
- Regenerated, e.g. viscose, modal, acetate

Figure 2.4. Synthetic fiber - crimped nylon
Source: www. feltingandfiberstudio.com

2.4.3. Fiber properties

Asides from the origin of fibers, there are a number of properties that are important for fibers in order to use them for the production of textiles. These properties can be divided into dimensional, physical, mechanical and general properties (Table 2.2)

Dimensional properties

The dimensional properties of strands that are determinant for the quality of the material are length, slenderness proportion (or fineness) and the shape of the cross-section. Longwise, it is critical that the strands are not shorter than 6-7 mm, in order to guarantee they can be utilized in yarn generation (Goswami, 2004). Shorter filaments can be utilized within the generation of nonwovens though.

Fibers ordinarily have a length to diameter proportion of 100:1. Finer filaments are simpler to twist, which results into yarns with higher flexibility and textures with soft handles, elegant drape, flexibility and more luster, due to a more prominent reflection of occurrence light without distortions. The fineness moreover decides the number of filaments within the cross-section of the yarn (Goswami, 2004).

Physical properties

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

Mechanical properties

A number of mechanical properties determine the performance of the fiber and as a result the textile, such as the strength, elongation, flexibility, recovery and bending stiffness (Goswami, 2004).

General properties

Other components that are vital characteristics in strands are friction, moisture and thermal characteristics. Grinding is vital since it is mindful for keeping together spun yarn, and for keeping woven yarns to preserve their position within the joining shape. On one hand, low frictional coefficients lead to destitute yarn strength due to slippage and on the other hand high frictional coefficients prevent handling (Goswami, 2004).

Moisture and thermal characteristics are relevant for the wear comfort of the resulting textile; water absorbing fibers help keep the skin dry and warmth retention helps keep skin temperature at an even level.

Some other factors that influence textile characteristics are softness, durability, abrasion, chemical and UV resistance.

2.5. TEXTILE PRODUCTION

Until the seventeenth century the textile production was mainly handled by women using natural fibers like wool, cotton, hemp, silk and flax. After the Industrial revolution the production process was automated due to the emerging technologies and methods for manufacturing. The first manufactured fibers (man-made) were developed in the late 19th century. Followed by the synthetic fibers late in the 20th century, the production escalated after the Second World War. The textile production is still developing in terms of new engineered fibers and unconventional methods for manufacturing and this is the quest of the new century - the creation of new fibers that are sustainable and functional, that can also be personalised easily to the needs of the users (Sinclair R., 2015).

The production process of textiles is characterized by creating a structure from different fibers (Figure 2.5). In this sense there are three main types of structures that can be distinguished: woven, knitted and non-wovens (Sinclair R., 2015).

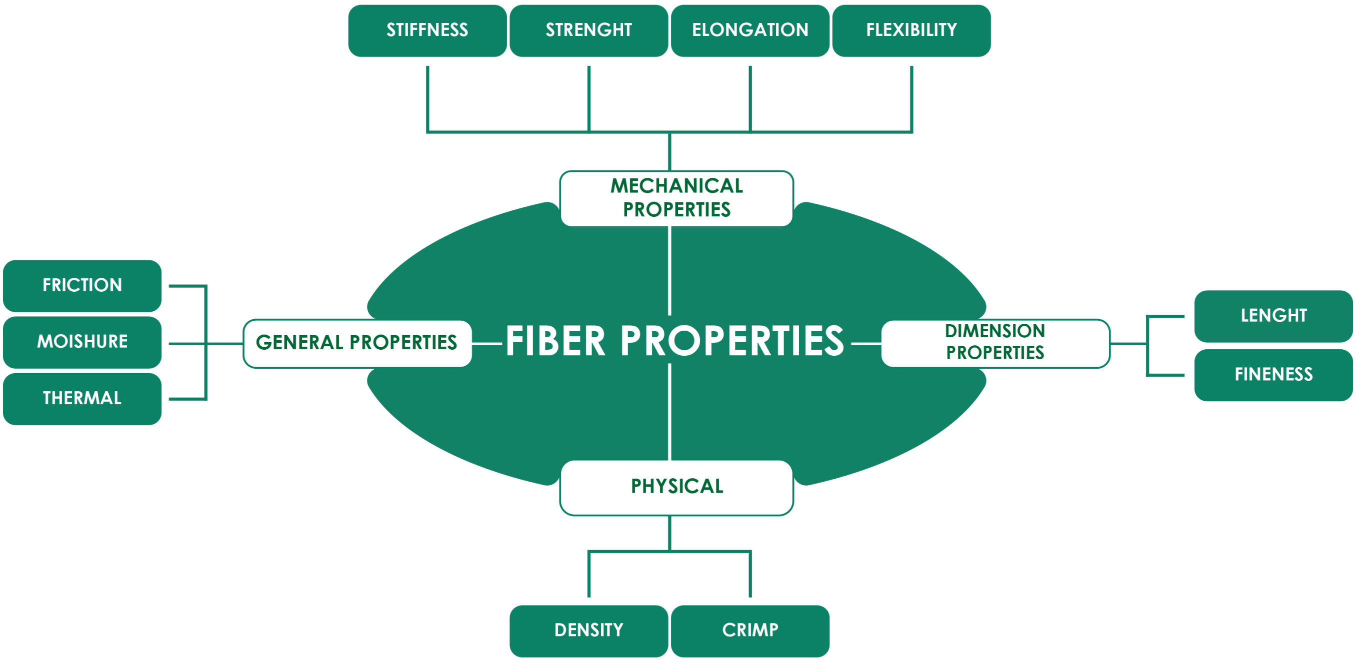


Table 2.2. Fiber properties

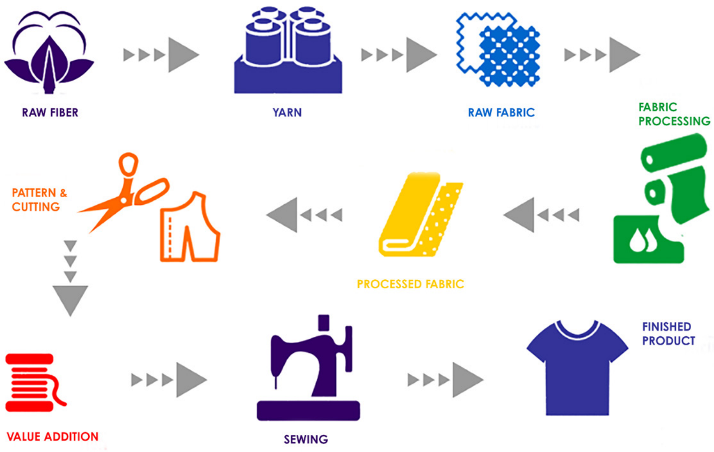
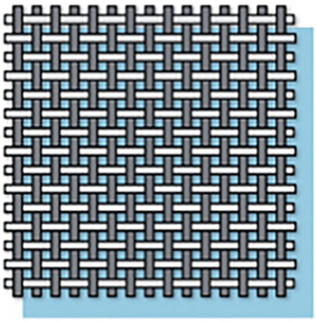


Figure 2.5. Garment manufacturing
Source: www.chinabrandscom

2.5.1. Weaving

Weaving is the method in which two sets of threads are entwining to form a level structure (Figure 2.6). The two sets of strings are called warp and weft, one is the running vertically and the other is the running horizontally (length and width, respectively). Due to the friction between the separate threads of yarn, the structure of the fabric remains intact. In hypothesis, an boundless number of weave structures can be created. The characteristics of woven textures, such as strength, stiffness, stability and porosity are decided by a few components, counting the sort of fiber (characteristic or man-made), the sort of yarn (thickness; mono/multi-filament; flat/textured; twist factor) and the density of weaving.In general, wovens are steadier and stronger than other material structures (Sondhelm, 2000). They are not so elastic, but are simpler to cut and sew than knitted structures.



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2.5.2. Knitting

The term knitting is utilized to allude to the development of a texture comprising interconnected circles of yarn. The resulting texture is flexible and permeable, able to supply warmth (due to the entanglement of air) and has delicate hanging qualities.

Knitted fabrics tend to stand up to wrinkling and are light-weight. Warp and weft knitting are two of the foremost common weaving strategies (Figure 2.7).

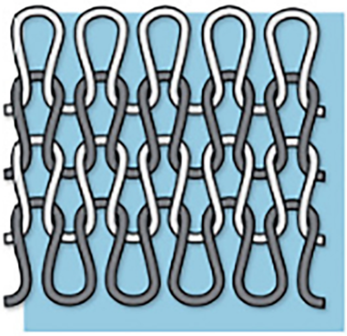

Figure 2.7. Knitted structure
Source: www.onlinelibrary.wiley.com

Knitted fabrics tend to stand up to wrinkling and are light-weight. Warp and weft knitting are two of the foremost common weaving strategies (Figure 21). The distinction between the two is the direction in which the string is fed. In a warp knitted fabric, the twist string is encouraged into the course of the texture (longitudinal), as in a weft knitted fabric the string is fed transversally (Carpi, , 2007).

There are numerous distinctive knitting machines, appropriate for diverse sorts of knits. One common ground is that the knitting fiber continuously should be overlapping or underlapping the other strings. The structure can be as complicated depending on the desired properties .

It is constructed from intermeshing loops. From literature, many diverse ways of creating the loops are known to exist but the origins of weft technique come from pin or needle knitting (Power, E.J., 2015).

Compared to woven fabrics, knits lack that stability, strength and flexibility but have greater drape qualities than woven. Moreover knitted structures are subject to relaxation, which permanently alters their geometry. Dry relaxation occurs right after production, and is caused by the fact that the tension applied during production is lifted from the yarns. Further relaxation during production can be achieved by soaking the textile in water and heating it. During use, relaxation occurs over time due to wear, washing or improper use.

Knitted fabrics characteristics are determined by the following factors:

- Structure of the knit: it has a significant effect on strength, porosity, bending rigidity (drape) and abrasion resistance. It also determines the aesthetic properties, the elasticity and the warmth of the fabric (Emirhanova and Kavusturan, 2008);

- Type of fiber;

- Stitch length;

- Yarn linear density, which determines the tightness of the fabric and inherently the drape.

Weft knitwear will continue to be prominent in fashion for the foreseeable future. Globalisation has and will continue to have an impact on the knitwear industry, as the low-cost labour countries experience the technology revolution. Many luxury retailers and designers are looking towards advances in technology to provide new innovation and open-niche marketing opportunities. The most sophisticated knitwear being designed and developed today combines the benefits of advanced materials with the latest innovative technology on the market, leading to cutting edge designs. Opportunities within CAD/CAM are yet to be exploited to the same degree of utilisation as in the automotive and industrial design industries.

2.5.3. Non-wovens

Nonwoven fabrics are engineered fibrous assemblies that are essential to the functional performance of products used in diverse medical, consumer and industrial applications as part of daily life (Figure 2.8). Historically, the nonwovens industry has evolved from different sectors of the textile, paper and polymer industries, and today it has a separate and distinctive identity. The main market segments for nonwoven fabrics in terms of volume are hygiene, construction, wipes and filtration.

Nonwovens are engineered structures of fibrous assemblies (such as fibers, continuous filaments, or chopped yarns of any nature or origin) that have been formed into webs by any means, and bonded together by any means.

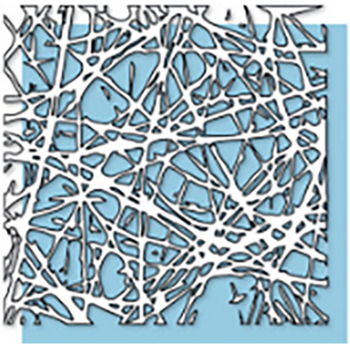

Figure 2.7. Knitted structure
Source: www.onlinelibrary.wiley.com

They appear to be vital to functionality of products related to medicine, consumer and industrial applications and many others (Russel S.J., 2015).

The evolution of nonwovens has taken place through a blend of various sectors such as textile, paper and polymer industries leading to an identity today. They are very well known for applications for hygiene, construction, filtration and wipes.

The main difference between non-wovens and knitted or woven fabrics, is the fact that the latter two are made out of yarn. Since yarn is not used for non-wovens, their production process is quicker and simpler (Duqesne, 2007). A nonwoven fabric structure is different from some other textile structures in the following aspects:

- It basically comprises individual filaments or layers of stringy networks instead of yarns;
- It is anisotropic both in terms of its structure and properties due to both fiber alignment (i.e. the fiber introduction dispersion) and the course of action of the holding focuses on its structure;
- It is ordinarily not totally uniform in fabric weight, thickness or both;
- It is profoundly permeable and penetrable (Russel S.J., 2015);

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

Consequently, a batt is formed by stacking a number of webs on top of each other. The production process from raw materials to bonding is often continuous (Smith, 2000).
The properties of nonwovens are dependent on a large number of factors, including the type of fiber, the bonding agent, and the orientation of the fibers. Smaller fibers are preferred for a number of reasons: they have a better filament distribution, which means the pores are smaller causing better filtration, a softer feel and lighter fabrics (Smith, 2000)

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

- Parallel laying: in which the fibers are placed in the machine direction (which is the length of the fabric);

- Cross laying: in which the fibers are oriented perpendicular to the machine direction (across the width of the fabric);

- Random laying: in which the fibers are oriented randomly;

Since the fiber quality is continuously higher than the quality of the holding operator, the heading in which the filaments are situated will be the most grounded course (Smith, 2000).

Commonly, non-wovens exist of networks of interlocking strands, that are reinforced by mechanical, chemical or thermal bonding (Smith, 2000; Patel, n.d.)

Mechanical bonding

In mechanical bonding, the strands are snared together. This is accomplished by utilizing needles to snare filaments or by-high-pressure water planes (Duqusene, 2007).

Chemical bonding

In chemical bonding, a a bonding agent is utilized and it is vital to choose it accordingly, since it decides the characteristics of the texture. Common bonding agents are butadiene copolymers, acrylates and vinyl copolymers. They can be utilized in liquid, foam or powder shape, depending on the utilized process. The utilization of different bonding agents will result in several material properties.

Thermal bonding

Thermal bonding employs heat as a primary strategy for bonding, and is based on the capacity of fibers to meld when exposed to heat (Duquesne, 2007). It is frequently utilized in addition to bonding processes.

Some processes, such as melt blowing, the strands are not fortified together at all, but just stick together. A polymer is utilized, which is blown into ultrafine fibers with hot air, after which they are cooled by cold air sprayed onto a surface. The filaments ought to be as fine as conceivable, in order to attain more fiber-to-fiber contacts to keep the batt intact (Smith, 2000).

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

2.6. PROPERTIES OF TEXTILES

In spite of the fact that there are numerous diverse sorts of materials, they have a number of properties in common that make them reasonable to utilize in articles of clothing. These properties can be categorised in three groups: aesthetic, functional and comfort properties (Table 2.3).

2.6.1. Aesthetic properties

Aesthetic properties relate to the appearance of the material. Appearance is of awesome impact on the term of utilization: once a piece of clothing loses its aesthetic appeal it is regularly arranged off.

Common components that adversely impact the appearance of materials are tearing, pilling (pilling resistance) and bursting strength (Emirhanova and Kavusturan, 2008).

2.6.2. Functional properties

Functional properties relate to the work the material should satisfy; for pieces of clothing this may be warmth retention or water resistance, but for specialized materials this may moreover be fire resistance and strength.

2.6.3. Comfort properties

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

- thermo-physiological comfort: which involves the transfer of heat and moisture through a fabric;

- sensorial comfort: the sensation felt when the textiles comes in contact with the skin;

- body movement comfort: the extent to which the textile allows freedom of movement;

- aesthetic appeal: the perception of the textile by all senses;

PROPERTIES OF TEXTILES

AESTHETIC PROPERTIES	TEARING PILLING BURSTING STRENGHT
FUNCTIONAL PROPERTIES	WARMTH RETENTION WATER RESISTANCE
COMFORT PROPERTIES	THERMO-PHYSIOLOGICAL SENSORIAL-COMFORT BODY MOVEMENT AESTHETIC APPEAR

Table 2.3. Properties of textiles

There is no consensus in literature as to what (combination of) properties are most important. Obviously, it will be different for every textile and function.

However, there is one property that can be seen as a requirement for textiles, which is flexibility. Without flexibility, it is not possible to create a wearable garment. Although this requirement seems obvious, it is often taken for granted as an inherent quality of textiles and therefore not discussed in literature related to comfortable textiles.

In any case, there are certain other properties that are frequently utilized when portraying materials, such as dra[e, handle and softness. Drape is characterized as the graciousness with which a texture hangs or wraps; a work of its resistance to bowing and its claimed weight (Emirhanova and Kavusturan, 2008).

Handle alludes to the whole sensation that is experienced when a texture is touched or controlled by the hands (Altas, 2013). It is related to properties such as flexibility, friction coefficient and surface properties. Delicate quality can be depicted by three perspectives: flexibility, compression and smoothness (Li, 2010).

These properties can be displayed in materials to diverse degrees, depending on the work of the piece of clothing.

For instance, a texture with high drapability can be used in a dress, but it isn't required when designing a blazer. Subsequently, they ought to not be seen as requirements, but as implies to depict the properties of textiles.

However, there are certain other properties that are often used when describing textiles, such as drape, handle and softness. Drape is defined as the graciousness with which a fabric hangs or drapes; a function of its resistance to bending and its own weight (Emirhanova and Kavusturan, 2008).

Handle or hand refers to the total of sensations that are experienced when a fabric is touched or manipulated by the hands [Altas, 2013]. It is related to properties such as flexibility, friction coefficient and surface properties. Softness can be described by three aspects: flexibility, compression and smoothness (Li 2010).

A list of properties for materials was collected from literature (Table 2.4) (Li,2010; Karana, 2009 and Goswami, 2004). Most of these properties or descriptors have a put to the 'comfort'- bunch, since they are related to what people encounter.

FLEXIBILITY

The ability of the textile to conform to the body.

SMOOTH	**SMOOTHNESS**	ROUGH
COARSE	**COARSENESS**	FINE
HEAVY	**WEIGHT**	LIGHT
COOL	**WARMITH**	WARM
STIFF	**DRAPABILITY**	PLIABLE
HARD	**COMPRESSION**	SOFT
ABSORBENT	**ABSORBENCE**	CLAMMY
LUSTROUS	**LUSTRE**	DULL
ELASTIC	**ELASTICITY**	NOT ELASTIC
POROUS	**POROSITY**	DENSE

Table 2.4. Key textile properties

2.7. CONCLUSIONS

By examining articles of garments, it has ended up clear that textiles are more complicated than they would appear on first glance. Materials are complex structures, impacted by a large number of variables. The properties of materials are mostly obtained by their progressive structure. On each level, the characteristics of the chosen material, process or structure impact the ultimate nature of the fabric. However, the generation from fiber to the last piece of clothing is extensive and comprises numerous steps, and for each step certain impediments happen, that are nourished all through the chain.

It isn't conceivable to certainly say what properties a textile needs to have, in order to be utilized for garments. It is necessary that the fabric must be flexible, in order to be able to comply with the body and leave room for development.

For the other properties, it was found that they depend intensely on the function of the garment. For occasion, denim and viscose are both materials with exceptionally distinctive appropriate ties, making them reasonable for distinctive applications (pants or jackets versus T-shirts and undergarments). Subsequently, the best application for a material depends on its appropriate function and vice versa. It is, in any case, conceivable to decide certain properties that can be utilized as descriptors for textiles (i.e. that can be utilized to depict certain characteristics of fabrics).

Therefore, these properties will donate an idea how to continue within the design of 3D printed textiles and what properties are ought to be accomplished, in the following chapters.

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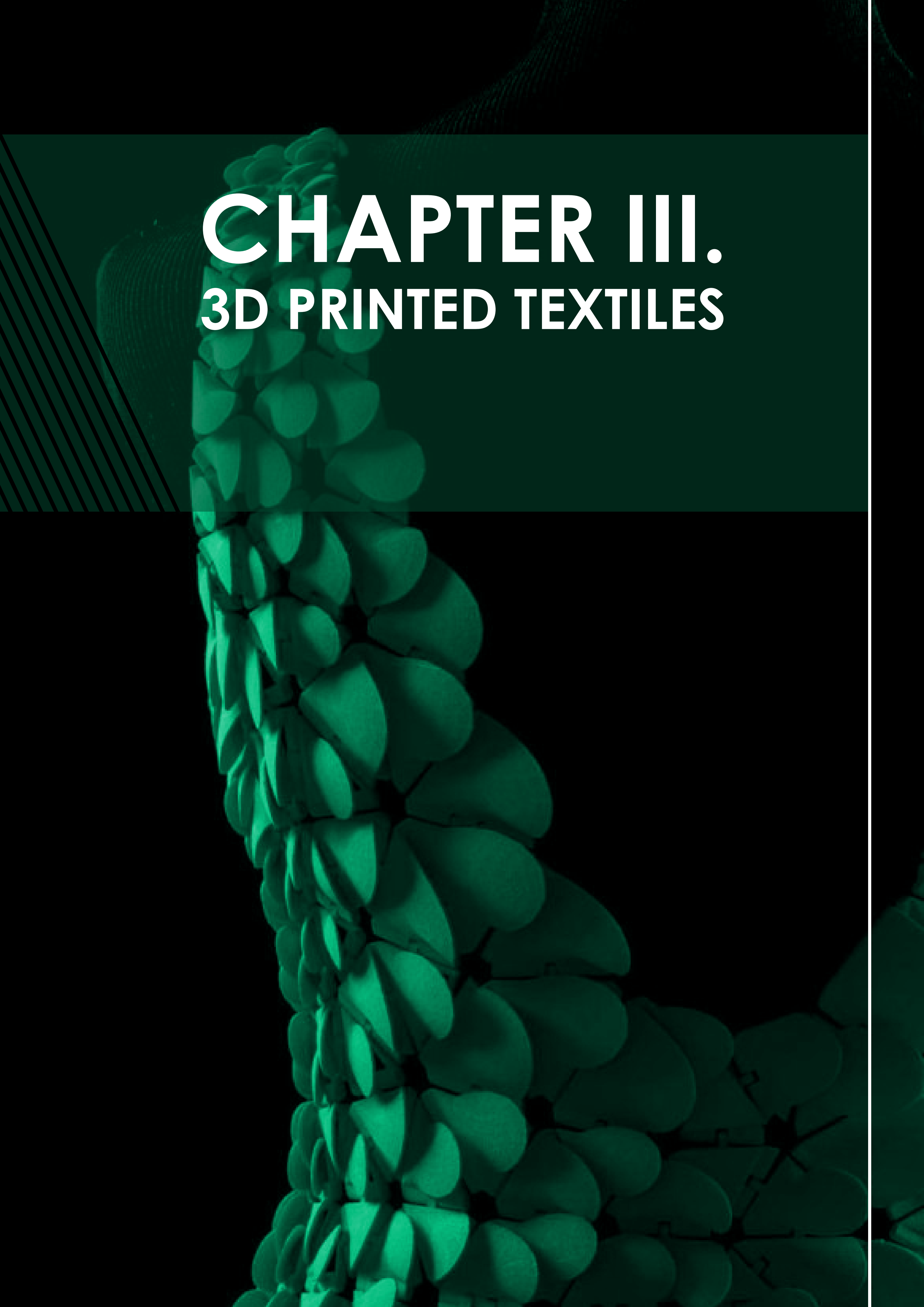
CHAPTER III.
3D PRINTED TEXTILES



3.1 INTRODUCTION

The 3D printing technology is increasingly used in the textile industry as it offers the decisive advantage of customised products, which are accessible to everyone due to the low cost. In addition, 3D printing can reduce complexity in the supply chain and reduce time to market by accelerating prototyping [Uysal. R., 2019]. It has been realised that it's potential is in the new complex structures unachievable with traditional manufacturing. Large apparel companies have already integrated 3D printing into their manufacturing processes. Although developing very fast, 3D printing is still on its initial page and it is facing big challenges in the choice of techniques and materials. Thus, the development of 3D printed textiles seems to be very difficult, resulting in the same wearing comfort and durability as conventional garments. Some studies have tried to combine the old and new technology. 3D printing on textile surfaces has been investigated allowing creating new multicomponent textiles and new optical properties. Here, the adhesion between both materials still remains challenging and has led to further studies to enhance the bonding properties between two diff erent materials due to fabric pre-treatment . [Uysal. R., 2019]

In the following sections already developed products will be analysed in terms of materials, production method and properties which will be compared to the traditional textiles. Constraints and limitations will be reviewed as well. This will introduce the world of 3D printed textiles and contribute for the next chapter where solutions, guidelines for design and techniques will be presented.

3.2. 3D PRINTED TEXTILES IN LITERATURE

The first proposed 3D printed textile was done by Evenhuis in 1999, co-founder of Freedom of Creations. Instead of using continuous fibers in sheet-form, a material was produced that consisted out of individual links. Since then, the use of individual, plastic links for the production of 3D printed textiles has been generally accepted, although no formal definition has been established.

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

- Decorative components: components attached to fabric/garments, without having a technical function;

- Functional components: components attached to fabric/garments and have a technical function. Examples of this are zippers and other types of closures;

- Accessories: fully printed objects, wearables such as jewelry or bags;

- Fabric-like: a 3D printed part that behaves like a fabric and can be used as such. This differs from partial garments;

- Partial garment: almost a full piece of clothing, although it still needs some alterations. An example of this is printing pattern pieces that need to be put together after printing;

- Full garment: a ready-to-wear garment that is completely printed;

In the following pages already designed garments will be reviewed in order to investigate the materials and properties;

BENCHMARK

N12 by Continuum Fashion

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

Source: kasteuk.wordpress.com

BENCHMARK

Source: www.n-e-r-v-o-u-s.com

Nervous system

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

BENCHMARK

Iris Van Herpen

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

Source: www.inspirationist.net

BENCHMARK

Loom dress by MARIA ALEJANDRA MORA-SANCHEZ;

Cosine Additive; Loom is an expandable, adaptable, wearable and flexible 3D printed dress designed by Maria Alejandra in cooperation with Cosine Additive (a 3D printing company). The dress combines textiles and additive manufacturing by applying materials and auxetic structures that consider function and the human body. The material is Thermoplastic Polyurethane (TPU) because of its elastic properties. The collection explores ready-to-wear auxetic (Auxetics are structures or materials that have a negative Poisson's ratio. When stretched, they become thicker perpendicular to the applied force. This occurs due to their particular internal structure and the way this deforms when the sample is uniaxially loaded) patterns which expand under longitudinal strain and contract when compressed. This behavior provides the swatches with various beneficial effects, unseen within the current swatches in the market. Their added value lies in form, function, and the geometric arrangements of the patterns (Alejandra M., 2018).

Source: www.mariale.design

BENCHMARK

Airwolf - 3D printed dress

It is also called A.X.I.O.S. stands for Dress Advanced Xtreem Integrated Operating Scales." It is made of an armor-like pattern created by designer Cameron Williams back in April 2014. Using SOLIDWORKS, Williams has modified this pattern slightly, to make it more appropriate for a dress design. It is 3D printed using about $78 worth of ABS, Wolfbend TPU, and TPE materials, and was designed and printed to be a perfect fit for Sandy's body. The model that is wearing the dress states that it is more comfortable than imagined (Aldughmin, 2015)

Source: www.3dprint.com

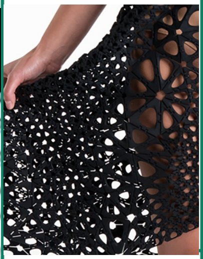
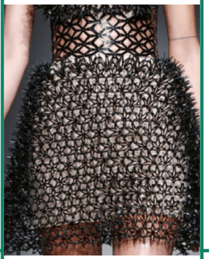
BENCHMARK

Drape dress by freedom of creation

The drape dress, created by Freedom of Creation, is made from a chainmail-like structure of interlocking rings. It is made out of nylon, and produced by means of Selective Laser Sintering (Freedom of Creation, 2006**)**

Source: www.fashnerd.com

BENCHMARK OVERVIEW

	CONTINUUM FASHION	NERVOUS SYSTEM	IRIS VAN HERPEN	FREEDOM OF CREATION	LOOM DRESS	AIRWOLF - A.X.I.O.S.
						
Type	Thin structure Nylon SLS	Multiple assembly Nylon SLS	Flexible material Polyurethane SLS	Multiple assembly Nylon SLS	Multiple assembly Nylon SLS	Multiple assembly Nylon SLS
Applications	Bikini	Dress Top	Dress	Dress Bag	Dress Bag	Dress Bag
Functional qualities						
Machine washable	No	No	Yes	No	No	No
Breathability	Medium	Medium	Low	High	High	High
Absorbence	Medium	Medium	Low	Medium	Medium	Medium
UV- resistance	Low	Low	Low	Low	Low	Low
Elasticity	Medium	Low	Medium	Low	Low	Low
Drapeability	Medium	Medium	Low	High	High	High
Experiental qualities						
Delicateness	High	Medium	Low	Medium	Medium	Medium
Softness	Low	Low	High	Low	Low	Low
Smoothness	High	High	High	Low	Low	Low
Warmth	Low	Low	Medium	Low	Low	Low
Lustre	Medium	Medium	Low	Medium	Medium	Medium
Sustainable issues						
Recyclable	No	No	Yes	No	Yes	Yes
Biodegradable	No	No	No	No	No	No
Renewable	No	No	No	No	No	No
Durability	Low	High	Unknown	High	High	High
Other emerging issues	Ready to wear	Conceptual	Haute couture	Ready to wear	Ready to wear	Ready to wear

3.3 CLASSIFICATION

Based on the benchmark three types of 3D printed textiles can be distinguished - those basing their flexibility on structure, those basing their flexibility on the material, and a combination of the two. Their characteristics are used to create an overlapping definition of 3D printed textiles (Figure 3.1): 3D printed flexible, textile-like structures.

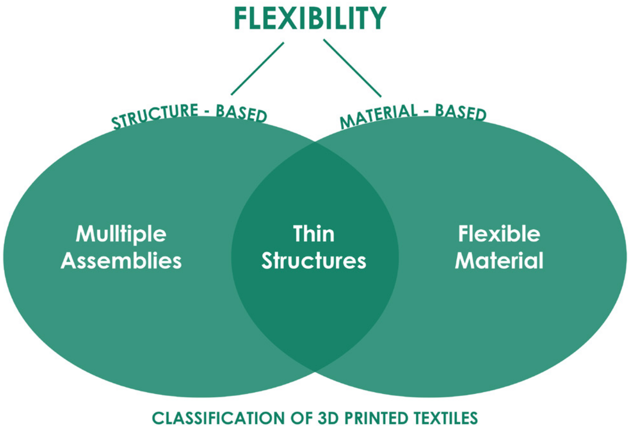


Figure 3.1. Classification of 3D printed textiles

3.3.1 Structure - based

3D printed textiles that base their flexibility on structure which is achieved by small interlocked parts creating multiple assemblies. Problems associated with multiple assemblies include (Hague, 2006):

- Limitations in CAD systems: the generation of large data sets, wrapping links over complex surfaces, collapsing the structure for efficient manufacturing;

- The resolution of the additive manufacturing process;

- Design of the links: 'buckling' of links can be a problem.

However, using an assembly of links also has certain advantages. The structure enables the production of a flexible sheet or product, made out of a rigid material. Also, due to the geometric possibilities provided by additive manufacturing, the links can be made into virtually any shape, to create patterns (some examples are shown in Figure 3.2) or to create differences in drape characteristics and freedom of movement [Bingham et al., 2007].

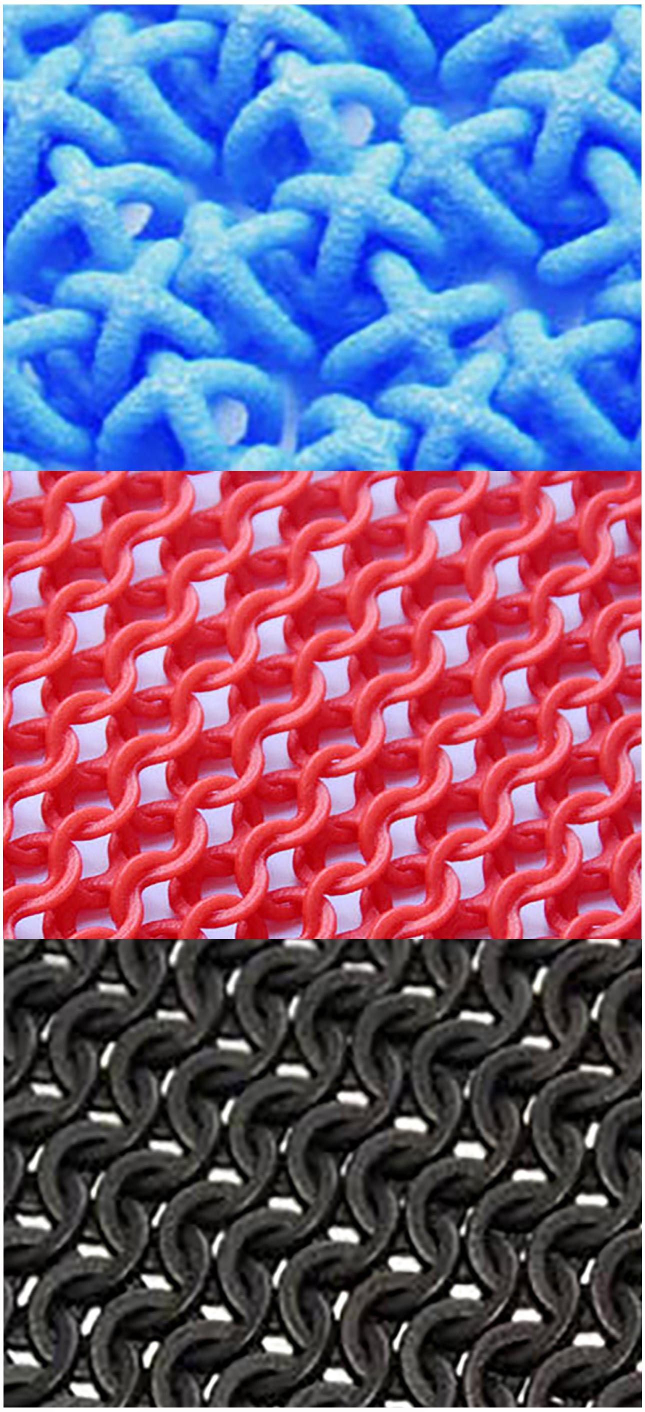


Figure 3.2. Multiple assembly structure
Source: www.architerials.com

Multiple assemblies exist in different forms, such as assemblies of links or integrated hinges (Figure 3.3). They are very suitable to be created by means of additive manufacturing processes, although not all processes can be used.

Figure 3.3. Multiple assembly structure
Source: www.pinterest.de

3.3.2 Material - based

Although multiple assemblies are currently the largest part of the 3D printed textiles market, there is also potential for them on more material-related principles. The flexibility of these 3D printed textiles is obtained by the characteristics of the (base) material, rather than by the structure. A lot of flexible materials are at the moment being developed for 3D printing. Flexible, rubber-like materials are now available for SLS, FDM and PolyJet technology. The biggest disadvantage of these materials is that they are quite weak (not tear-resistant) and often difficult to print with good results.

3.3.3 Thin structures

An overlapping category can be distinguished which uses both material- and structure-based principles, named thin structures. Thin structures have not yet been applied a lot as 3D printed textiles. As with flexible materials, they can be produced as one part, however they require a special structure to impart them with flexibility. Examples of this are very thin sheets of plastics, which are flexible because of the thin structure they have, but also because the material has some inherent flexibility. Polymers and metals are good examples of materials that allow themselves to be used for thin structures. One example of thin structures applied as 3D printed textiles is used in the N12 Bikini by Continuum fashion, reviewed in the benchmarking.

3.4 MAIN TECHNICAL PROPERTIES

Although stiffness and texture are important characteristics of textiles, they remain a challenge to fabricate using current FDM. Thus, researchers have created deformable objects consisting of microstructures. Meanwhile, textile has become a promising material presenting the possibility of integrating its unique flexible and soft properties when fabricated or embedded into a rigid object.

The main technical property of all 3D printed textiles is flexibility, as previously discussed. Per definition, flexibility is the complementary concept of stiffness – therefore the less stiff the material, the more flexible it is. As a result, it is possible to recognize varying degrees of flexibility in the 3D printed textiles. It is important to realize that the flexibility is largely influenced by the structure; for instance the chainmail-like structure of Freedom of Creation is more flexible than Iris Van Herpen’s dress as a flat sheet.

What also can be seen from the examples shown in the previous chapter is that some have a large macro-structure, which allows the material to be more breathable. This is an important attribute in textiles, as was found in the previous chapter.

Another very important and crucial property is drape. It allows a fabric to be bent in any direction by creating different beautiful folds. It is important for garment design and the selection of the appropriate material for a specific product. However, not many reports about 3D printed textiles can be found, although especially 3D printing allows changing the mechanical properties of a textile fabric.

Drape is influenced in various ways by 3D printing different geometrical patterns. The experiments which Spahiu et al 2017 reported, show that for all patterns, drape was found to be influenced significantly by the 3D printed patterns, especially by the free spaces between the imprinted areas as well as the overall areal weight of the fabric (Spahiu T., 2017).

In the next chapter study cases will be analysed in order to compare the 3D printed textiles properties with traditional textiles.

3.5 MATERIALS USED IN 3D PRINTING TEXTILES

The type of material used for AM is important and it is directly influencing the objects dimensions, durability, characteristics and possible applications as well as the willingness to wear the cloth-like structures. Lightweight polymers or polymer composites are the main materials used as printing materials allowing flexibility of the printed items. The most current materials used for AM textile structures are usually not flexible enough to provide suitable comfort for daily use. Their selection is limited from the printing technique. For providing thermo-physiological comfort, natural textile fibers on cellulosic or protein basis still would be ideal materials. Some researchers try to use wool as printing material to overcome the limitation of plastic materials, but in this case the process is not presenting the 3D printing using polymer deposition. Wool and cellulosic fibers have no melting point,and because of that their direct use for 3D printing by melting is not possible.

In general, the raw material for printing can be in three states - solid/powder, liquid and gas. The type of the material varies from polymers, metals, ceramics, waxes, sand, resins and a composite of two or more materials. Of course, the polymers are dominating in the past years, followed by resins and metas, due to the wide range of properties that they can provide in different fields (Kyosev. Y., 2020).

The most commonly used polymers are thermoplastic polymers like PLA (polylactic acid), ABS (acrylonitrile butadiene styrene), PETG (polyethylene terephthalate glycol-modified), nylon (polyamide), and TPU (Polyurethane), acrylonitrile-butadieen styreen (ABS), polyurethane and photo-acrylic (Kyosev. Y., 2020).

It can be seen that the used materials have very different properties that determine the way in which the material can be used to create flexible structures. Most materials have poor UV-resistance, especially the ones that are cured by UV-light (SLA and PolyJet)(Kyosev. Y., 2020).

This means the lifespan of a garment that is worn outside could be significantly reduced, by alterations in aesthetics as well as mechanical properties, although this is also true for traditional textiles.

Researchers have predicted that more textile related materials will be developed and used in the future. For example, TamiCare Limited (www.tamicare.com), has already developed an AM technology called CosyFlexTM that can print fabrics using liquid polymers, including natural latex, silicon, polyurethane, and Teflon, as well as textile fibers like cotton, rayon and polyamide.

Another textile company trying to implement a new method of production of textiles is Electro-loom (www.kickstarter.com). With the use of an electro-spinning method, the liquid polymers are sprayed out from the nozzles and then dried to form the cloth on the 3D mold of the shape. Unfortunately the company closed in 2016 because of financial and technical difficulties (www.engadget.com).

Electrospinning is a modern method for production of fibrous surfaces with very fine materials, which can be suitable for tissue engineering and other special areas, but their productivity is still very low for conventional clothing (Kyosev. Y., 2020).

The materials for additive manufacturing based on electro-spinning are not discussed here, because they cover large set combinations of materials and solvents and they are not the subject of this paper.

Another interesting trend in materials is composite filaments of two components. They can be reviewed in two groups based on the fiber length (Kyosev. Y., 2020):

- Short fiber content materials - very short fibers, for instance carbon fibers are mixed within the thermoplastic polymer.These materials combine all advantages of the short fiber composites and the 3D printing which allows the production of complex 3D parts with better properties based on the reinforcement of the short fibers
- Continuous filaments - a core with multifilament from glass, aramid or carbon is covered for instance by nylon. These filaments require integrated scissors devices close to the nozzle in order to be able to cut at the predicted places. The materials can provide significantly efficient part design because the filaments can be placed in the required directions and places and the remaining part can be printed with lower density pure polymer solution;

3.6 PRODUCTION METHODS

The currently dominating process is Fused deposition modeling (FDM), followed by selective laser sintering (SLS) and stereo lithography (SLA), respectively. These are the main types of 3D printing technologies used in relation to textile context: FDM for printing onto a textile fabric, SLS for producing textile-like structures and SLA types used to form fabric-like textiles which can be rolled and seemed to shape. Table 3.1 gives a brief description of them with the materials, textile products, advantages and disadvantages (Kyosev. Y., 2020).

TECHNIQUES	MECHANISM	MATERIALS	ADVANTAGE	DISADVANTAGE
Stereolithography (SLA)	Photopolymer resin, and an ultra-violet (UV) laser to cure and harden individual layers to form objects. Rigid parts and connective joints can be printed together at one time.	Polyethylene, polypropylene, ABS, polycarbonate casting and molding material A flexible, elastomeric material can be combined with stiff and hard polymer. 3D printedtextiles are stiff and not flexible.	Fast printing process. More flexibility and texture; offers high-quality surface finish.	Requires support rafts, additional time, sanding and reduces the quality of the product due to sanding; expensive material and no color variety.
Selective laser sintering (SLS)	A computer-controlled laser traces the layer, heating the powder to just below its boiling point to fuse the particles into a solid object. After the first layer is created, the building platform drops, exposing the next layer of powder.	Only use one material per model; multi-material models printed separately and joined afterwards. Glass, plastic,metals, ceramics, or nylon, stainless steel, titanium alloy, nickel alloy, aluminum,copper. Dresses, bathing suits, shoes, single and double face knits.	Allows designers to create delicate, yet highly functional and durable products.	It does not produce a high-quality surface finish compared to SLA.
FDM (Fused deposition modeling)	FDM offers a variety of low-cost desktop printers. Based on heating a filament in an extruder nozzle and depositing the molten material line by line on a printing bed where it hardens. The next layer is printed on top of the previous layer.	Wax, metals, ceramics, acrylonitrile butadiene styrene (ABS), polylactic acid (PLA), polyethylene terephthalate (PET), aramid, onyx, glass and carbon fibers are some. Shoes, skirt, dress, jacket, soles, yarn, knit structures and printing on and with textiles.	Capable of printing flexible, glossy, lace-like fabrics with soft PLA polymers.	Visible seam lines between layers and delamination from temperature changes, influence the strength of the bond between layers.

Table 3.1. Processes used in 3D printing textiles

3.7 LIMITATIONS

As every production process, 3D printing has its drawbacks. The main reason for this is the fact that 3D printing was not developed for the fashion industry purposes. Its main aim is not for garment manufacture till now.

3.7.1. Materials

One of the main limitations for 3D garment printing are the available materials on the market. Due to the drapability, stretchability and comfortability requirement of a garment, the filament material used for 3D garment printing needs to be flexible and absorbent (Valtas.A.,2016).

However the filaments for 3D printing are far from the above mentioned property requirement. The printed 3D garments are fairly strong and water-resistant and they cannot be treated like many popular materials we use daily such as cotton and silk. Textiles printed with these filaments cannot be machine washed, ironed or pressed (Valtas.A.,2016). They lack in absorbency and cannot be sewn. When purchasing garments people see values of garments made of 100% wool, linen, silk which provides comfort to the wearer. Wearing a rubber like garment for daily wear would not be a good choice. Rubber like material is seen to be used for footwear and accessories. Therefore to produce 3D printed garment there is demand to develop new filaments to meet property requirements of textiles (Valtas.A.,2016).

There is no prerequisite of how the 3D printing materials they are designing will move or react as it would be in traditional fashion. The 3D printing materials are new and this knowledge must be built by testing alongside designing in 3D, only then can the designs work to their greatest efficiency, otherwise it is designing blind. Not knowing how a material reacts to movement or certain shapes and structures is a design faux pas as it would most likely result in an unsuccessful print.

The possibilities for 3D printed textiles are limited by the parameters of the 3D printing process. It was found by means of a number of explorations that the smaller the macro-structure of the material, the more it resembles a regular textile. Currently, the scale of the structure is limited by the possible minimum wall thickness that is allowed by the material and process (shown in Table 3.2). Also, there are a limited number of materials available. All materials that have been used so far for 3D printed garments are plastics. This is not a strange choice for textiles, since a lot of fibers are made of synthetic polymers (as discussed in chapter 2).

However, currently there is no possibility to print natural materials, such as cotton and wool. Lastly, since the additive manufacturing processes that exist today were not developed with the specific goal to produce textiles, it is hard to say whether these are the ideal processes.

3.7.2. Manufacturing process

As 3D printing was not necessarily invented for garment manufacture initially, a lot of the available software does not allow the technical means needed when creating a 3D file for a garment. While a lot of programs nowadays allow visualizing garments on a 3D human body, none of them currently have the ability to design onto a human body and extract the design as a ready printable STL file (Valtas.A.,2016).

FDM FUSED DEPOSITION MODELING	PET	USES RPET A RECYCLED POLYESTER AND LOW COST	NOT HIGH QUALITY PRINT AND VERY BASIC
LASER SINTERING	TPU	FINE DETAIL AND FLEXIBILITY CAN BE ACHIEVED	CURRENTLY NO RECYCLABLE MATERIALS AVAILABLE & HIGH COST
SLA Stereolithography	ACRYLIC	FINE DETAIL AND LESS FINISHING CAN BE ACHIEVED	CURRENTLY NO RECYCLABLE MATERIALS AVAILABLE & HIGH COST

Table 3.2. Limitations

In many cases, the designing process is lengthy and tricky, and limited to the availability of the printer.

3.7.3. Knowledge

Another limitation are the skills of the designer of these files, but even with the help of skilled professionals, he would face a lot of issues, which would not be welcome at a mass manufacturing level (Valtas.A.,2016).

Directly opposite to the Fashion designer, the Product designer has no or little fashion knowledge in terms of design and what may fit etc., however, they have designed things in the past that fit the body such as caps but may not have necessarily designed products that need movement like clothing does. Also knowing what suits a person fashion wise and what details may work to be aesthetically pleasing isn't the key when designing a product (Grain, 2016). Table 3.3 represents the process alignment between commercial fashion design and fashion design when using a 3D printer. The first diagram is what was planned to take place and drawn up before any of the 3D work had started, then the second diagram is what actually took place. The difference is huge due to the fact that with traditional fashion design, the designer would know the materials they were working with and how to design for those materials but did not have to first design the textile material itself. With the actual process, because of its infancy, not enough pre-existing 3D printing textiles exist to design from, therefore the project started at the point of textile design and not of garment design as it would traditionally.

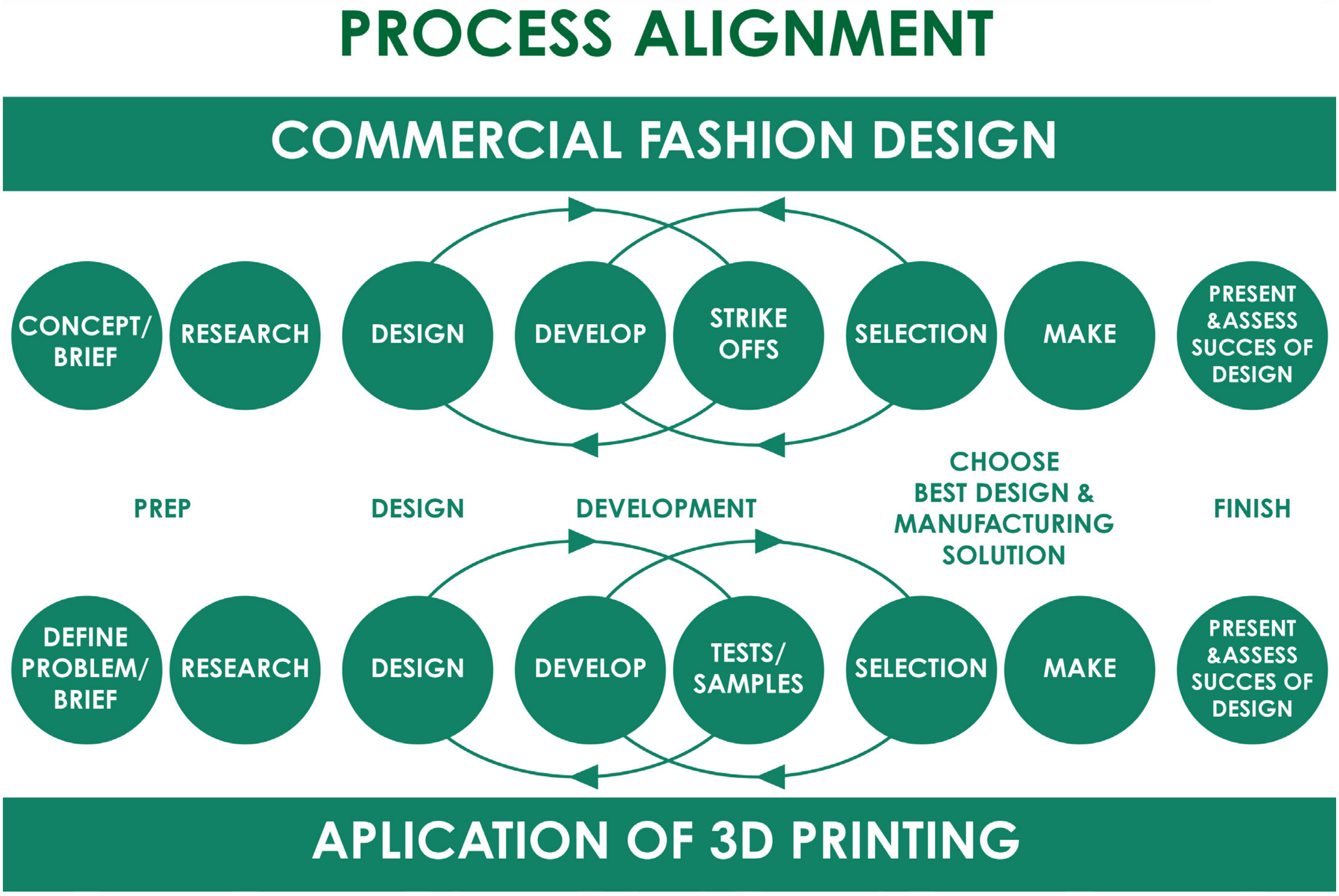


Table 3.3. Process alignment

More research and innovation in this area over the next few years will increase the availability of pre-existing textiles to print out into the shapes of wearable designs, but until then the researchers must start from scratch and design new structures for the materials we have to work within this area and work with their properties and constraints as this is not fabric anymore.[Grain, 2016]

3.8 CONCLUSION

This review demonstrated that additive manufacturing already influences the textile production in many directions. One direction is the 3D printing on textiles, where additional features to the existing textiles can be added and customized and personalized products can be quickly created.

The printing of flexible structures based on rigid materials is another area, where the structures try to have some “textiles like” properties, and will definitely find their application for complex structures in robotics, fashion, architecture and will replace some of the existing heavier and solid products, but they are not real competitors to textile products.

The area with least developments is printing with flexible materials. It is in a very early stage but it can be expected in the future for a rapid development of new elastic materials. They will enhance the properties of the 3D printed textile-like structures in terms of good air and moisture permeability. Nevertheless, several tasks have to be solved near the properties, which are required for thermo-physiological control, to stabilize printing conditions. In addition high production speed and lower costs have to be reached, in order to become serious competitors to textiles.

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CHAPTER IV.

CASE STUDIES

4.1. INTRODUCTION

In previous chapters it has been explained the structure and properties of traditional and 3D printed garments. It has been found that the property with highest importance is flexibility and there are different methods (FDM, SLS) and materials which can be used accordingly.

In this chapter several study cases will be reviewed in order to explore different approaches and techniques for achieving flexibility in 3D printing of textiles.

4.2 MODECLIX: The additively manufactured adaptable textile

Creating flexible materials by additive manufacturing techniques continues to be both challenging and rewarding. Modeclix is a research project that addresses the challenges through combining both traditional construction techniques with advanced manufacturing technologies. It consists of a system of additively manufactured links that can be manufactured as linked panels but the design of the link allows for the panels to be de-constructed and then reassembled by hand (Bloomfield M.,2018). It allows a range of different shapes to be constructed, with no size restrictions that is often a defining factor of AM technology.

On the one hand Modeclix is used to create a range of clothing and fashion accessories to demonstrate the versatility of the linking system. The sheets of linked textile are designed to be printed in polyamide (Nylon PA12). The material can be post processed and then dyed in a range of colours so that patterns and designs can be incorporated into the textile form. As the textile consists of interchangeable links it is a straightforward process to repair and re-purpose the textile (Bloomfield M.,2018). For example, garments can be made to fit the customer simply by removing or adding links to adjust the size and shape, satisfying the emerging demand for bespoke fully fashioned products. Modeclix reduces usage of resources through localised production, product life extension and demand driven manufacture that's both customisable and scalable. It represents an innovation in the use of 3D Printing to produce a flexible material that is infinitely configurable to meet a range of different demands. The rationale behind the project is to create a fluid 3D Printed textile (Bloomfield M.,2018).

The modularity of Modeclix enables an ecosystem that can efficiently re-use and or re-purpose the material across a variety of different products and services (Figure 4.1). As the majority of the construction processes are initially undertaken by hand, emission and energy concerns are naturally reduced (Bloomfield M.,2018).

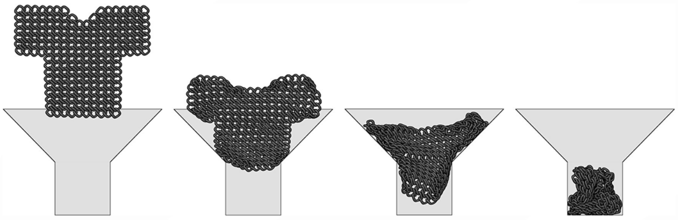

Figure 4.1. Re-use of the material
Source: Blomfield M.,2018

Methodology

A 3D printer is used for the purpose, in this case is a Plastic Laser Sintering System, the Formiga P 110 from EOS, with a total build area of 200×250×330mm and it was selected because of the characteristics of the material; white polyamide PA12-powder (Nylon) (Bloomfield M.,2018).

The first approach was to design a range of linked configurations using CAD software and produced additively manufactured test pieces to explore the idea. It was discovered that the digital designs became complex to create and edit in the CAD software, particularly as it was wanted a small link to get maximum fluidity out of the final textile (Bloomfield M.,2018).

Another approach was tested including the use of a physics solver to calculate the position of links when using gravity to fill a virtual volume that matches the build area of the AM machine.

The reason for not perusing the physics folding method was not only due to the possibility of the links failing, but also once the garment had been made and it was discovered that it didn't fit the customer or they didn't like it, it would prove to be a wasteful exercise. The garment would then have to be disposed of as it could not be repaired or adjusted (Bloomfield M.,2018).

Based on the experimentation it would be beneficial to create a material that wasn't dependent on CAD expertise and that could be repaired if the AM process failed. This evolved in another solution which solved the issue.

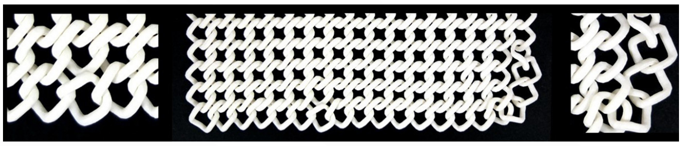

Figure 4.2. System of links
Source: Bloomfield M.,2018

The system of links can be additively manufactured as linked panels (Figure 4.2). However, the design of the link allows for the panels to be de-constructed and then reassembled by hand. Linked panels can be connected together and manipulated by hand to create form and shape easily without any CAD expertise. The linking system enables large forms to be constructed. This is crucial as it removes the issue of the size restrictions defined by the model of AM machine used (Bloomfield M.,2018).

A link consists of 4 connected spiral arms. The links are connected across the top face, but left open on the reverse, to allow the links to be disconnected and reconnected as required (Figure 4.3). The link measures 9.5×9.5×3.6 mm. Each arm of the link is 1.4mm diameter and the total size of the link takes into account the need for a 0.4mm gap between links when linked together in the CAD software. This allows sheets of linked material to be manufactured without the links fusing together as they undergo the sintering process (Bloomfield M.,2018).

The possibilities of the system and material give certain advantages:

- The links can be connected into an array of different configurations.
- Modeclix consists of interchangeable links, the repair process is straightforward
- Modeclix can also be re-configured. This means garments are completely and fully customisable.

The potential to develop the system further through new component parts will also ensure the adaptability and future usability of the textile.

Future development will entail looking at the built environment to explore the use of Modeclix as a screening material, upholstery for furniture and temporary architectural structures. Modeclix also addresses the need to reduce resources through localised production, product life extension and demand driven manufacture that's both customisable and scalable. Modeclix also reinvents itself with each new application (Bloomfield M.,2018). As new components are introduced that work with the link system, this excites the market through new possibilities that allow all previous Modeclix components to be repurposed and reused creating a sustainable future for the material. Modeclix is a registered trademark of the University of Hertfordshire Higher Education Corporation (Bloomfield M.,2018).

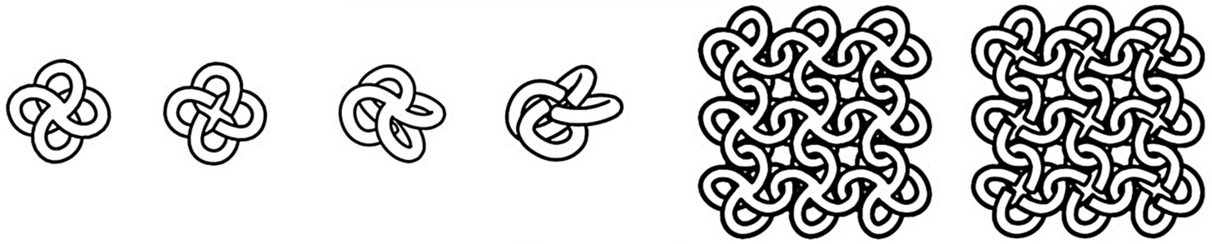

Figure 4.3. A single link on the left and connected links on the right
Source: Bloomfield M.,2018

Source:www.modecliix.com

4.3 DEFEXTILES: 3D Printing Quasi-Woven Fabric via Under-Extrusion

This project called DefeXtiles, is a rapid and low-cost technique to produce tulle-like fabrics on unmodified fused deposition modeling (FDM) printers. The under-extrusion of filament is a common cause of print failure, resulting in objects with periodic gap defects.It is demonstrated that these defects can be finely controlled to quickly print thinner, more flexible textiles than previous approaches allow. The approach allows hierarchical control from micrometer structure to decameter form and is compatible with all common 3D printing materials (Forman J.,2020).

Methodology

DefeXtiles are lean, adaptable materials of numerous materials that can rapidly be printed into an assortment of 3D shapes utilizing a cheap, unmodified, 3D printer with no extra computer program (Figure 4.4) (Forman J.,2020).

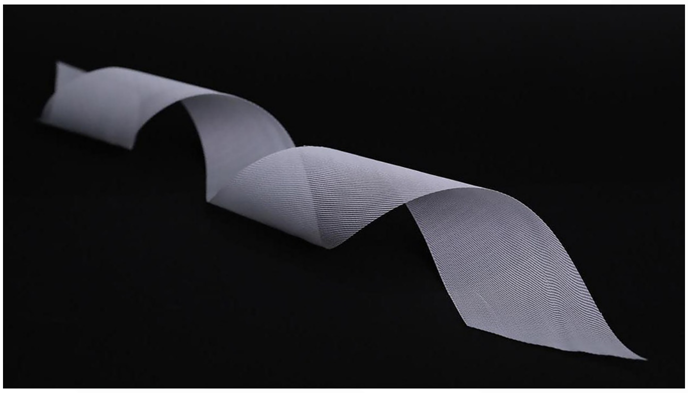

Figure 4.4.3D printed textile
Source: Forman J.,2020

This is often accomplished by utilizing the fabric properties to encode the material frame: particularly utilizing the periodic gaps that develop when material is insufficient to print.

The printer moves and prints the same because it would be a solid,rigid sheet, but by leveraging the stringing behavior that occurs in thermoplastic filament it is able to encode little crevices that manage the stretchability and adaptability (Forman J.,2020).

Manufacturing of 3D forms out of textiles has remained largely the same over the years - fiber becomes a fabric which is then constructed into a 3D object. Knitting has made a considerable advance in changing this paradigm as the fabric and form can be generated simultaneously. Inverse design pipelines for machine knitting have further shifted the nature of textile construction towards the computational production of fully shaped textiles. Despite these advances, the ability to generate complex 3D forms with textiles outside of industrial manufacturing settings remains elusive. The high-tech approach, machine knitting, currently uses expensive machines with a significant learning curve for programming. The low-tech approach, classic sewing, requires skilled and practiced hands to carry out pain-staking processes such as draping, tracing patterns onto fabric, adding seam allowances, and sewing (Forman J.,2020).

Fused Deposition Modeling (FDM) is the most common and inexpensive approach for 3D printing. In this technique, a material, most often a thermoplastic filament, is melted and deposited by a heated, moving printer extruder head to build up an object layer by layer. In order to yield successful prints, the speed of the nozzle head, and amount of material extruded must be carefully coordinated to yield uniform layers.

The most common parameter used to fine tune this coordination is the extrusion multiplier (EM). For example, setting the EM to 2 will double the amount of material extruded through the nozzle, and setting the EM to 0.5 will halve it. Over-extruding material can cause excess buildup of material on the corners of prints, and under-extruding material can cause gaps to form between layers (Forman J.,2020).

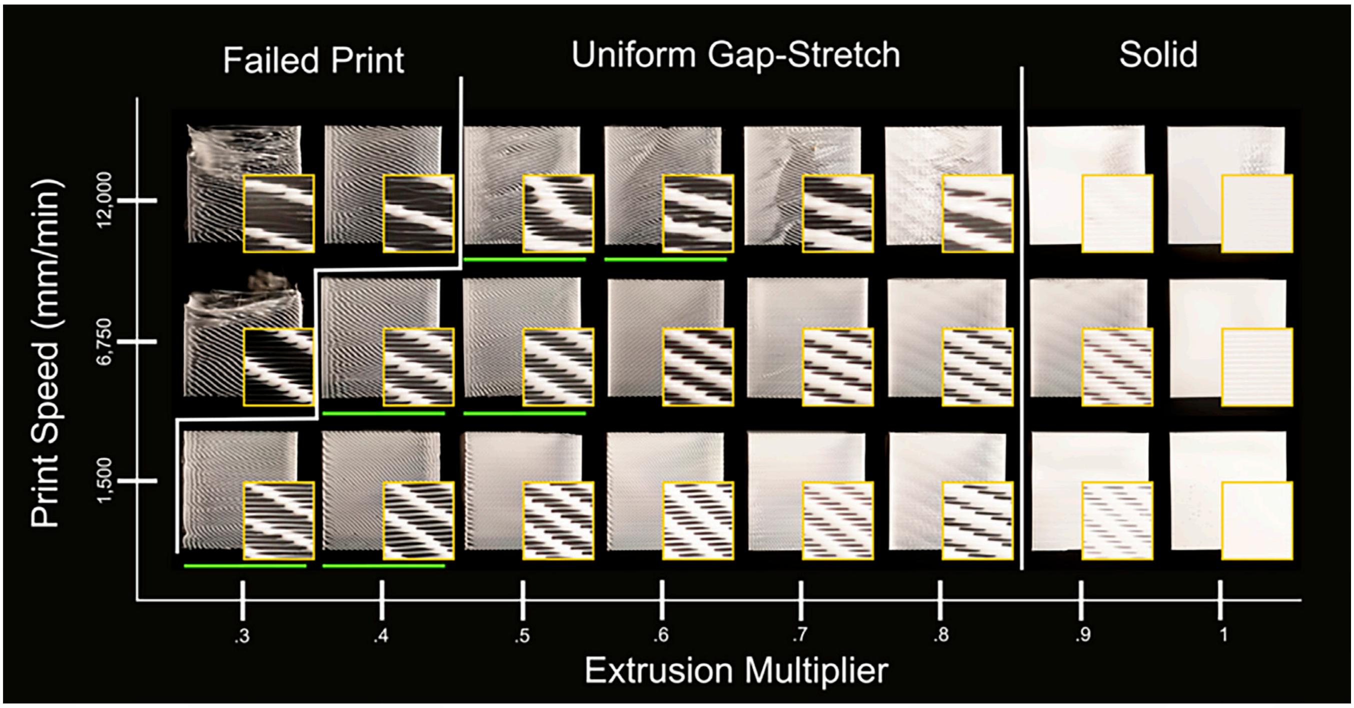

Figure 4.5.Resulting structure of PLA prints with different extrusion multipliers and print speed. The underlined green samples are our recommended values.
Source: Forman J.,2020

It is demonstrated that under-extrusion can be leveraged to quickly print thin, flexible, textiles. Specifically, as the extrusion multiplier decreases, there exists an ideal regime where globs form with fine strands connecting them as seen in Figure 4.5 (Forman J.,2020).

The glob-stretch phenomena that occurs in DefeXtiles is not due to the material used. In fact many materials for 3D printing can be used with this technique (Forman J.,2020).

After a characterization it has been found that TPU has the best combination of strength and flexibility and is well-suited for applications where durability is needed.

However, outside of these applications it is not recommended to use TPU as it is a tricky material to print with, requiring exact calibration of first layer height and extrusion multiplier. It was also determined that a PLA DefeXtile could withstand a 900g load along the z-axis before failure.

Both PA and PLA are easy to print alternatives with a balanced combination of traits. Annealing PLA resulted in a notable improvement in weft tensile strength but became less flexible (Figure 4.6). This is likely due to the thermal shrinkage of the PLA causing the sample to thicken. Another note is that the process of annealing can cause sample deformation, so it is probably not suitable for 3D shaped textiles (Forman J.,2020)

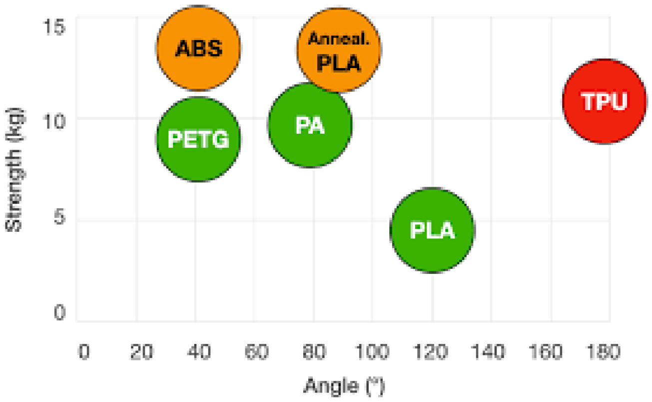

Figure 4.6. Measured properties of each material. Red, orange, and green indicate high, moderate, and low difficulty of printing, respectively.
Source: Forman J.,2020

A new approach was introduced in order to quickly print thin, flexible textiles composed of common 3D printing materials with an unmodified 3D printer. Properties such as flexibility, width and breathability are combined in 3D printed textiles.. Through characterization, it was proved how this approach enables tuning of the mechanical and aesthetic properties through material and parameter selection. Through a series of applications, we demonstrated the potential applicability of the technique for smart textiles, tangible online shopping, toys, fabric design, and everyday life. Due to the widespread use and accessibility of FDM printers, this approach can immediately empower a wide audience with the ability to fabricate fabric into finished forms (Figure 4.7).

Figure 4.7. 3D printed scirt
Source: www.3Dprintingindustry.com

4.4. A New Method of Printing Multi-Material Textiles by Fused Deposition Modelling (FDM)

The 3D printing technology is increasingly used in the textile industry. Additive manufacturing can reduce complexity in the supply chain and reduce time to market by accelerating prototyping. The creative minds of the textile industry have quickly realised that the potential of 3D printing lies in the development of new structures that cannot be achieved with common processes. This study is focused on creating textile-like surfaces by using the FDM technology and led to the development of a new printing method. The new printing method combines different materials into one structure similar to that of a conventional textile along with its properties like flexibility (Uysal R., 2019).

Methodology

A new 3D printing method was developed that influences the printer’s behaviour from the sketches. In this sense the sketches were made in Adobe Illustrator by taking specific units of measurement into account and then processed into 3D models by using the animation software Blender. Afterwards, the 3D models were scaled and placed in a print position in the CAD software Autodesk Netfabb. Simplify3D was used to slice the STL files (Uysal R., 2019).

Several print settings were made to optimise the print results. The 3D models were printed in the Prototype Development and 3D Print Lab (PD3D) at the University of Central Florida in Orlando. Two FDM printers were used. Models made of two different materials were printed with the 3D printer X400 (German RepRap GmbH, Feldkirchen, Germany). Models made of more than two different materials were printed with the 3D printer CR-10 (Creality3d, Shenzhen, China) in combination with Palette 2 Pro (Mosaic Manufacturing Ltd, Toronto, Canada).

For printing, the filaments PLA (Hatchbox 3d, Pomona, CA, USA) and LAY-FOMM 40 (CC-Products, Cologne, Germany) were used. In the last step, the printed models were post-treated (Uysal R., 2019).

The following steps of printing are illustrated in Figure 4.8. This model was printed from two different materials and consists of 11 layers. This basic structure consists of several parallel strands with varying orientation in different layers. It was printed from the material LAY-FOMM 40. The rest of the layers are printed with PLA. All layers are coordinated with each other and together form a system of structures. If a polygon surface is printed on another polygon surface during the printing process, the two join through the thermoplastic process and enclose the strands in-between. The strands connect the polygons and result in a coherent structure in which both materials cannot be separated from each other (Uysal R., 2019).

The choice of the pattern influences the properties of the textile-like surface. A patterned surface of polygons (4 mm × 3.5 mm each) is showing a different drape than a repeating pattern of rectangles (3.3 mm × 3.3 mm each). Larger patterns (23.1 mm × 22.5 mm each) were also used; the larger the pattern, the more rigid the textile-like surface became. The size of the repeating pattern also has a large influence on the printing time of the model. The smaller the pattern, the longer the printing process takes (Figure 4.9) (Uysal R., 2019)

The flexibility of the surface could also be influenced by the number of layers and especially by the number of connecting strands. The more connecting strands the structure contains, the more rigid the surface becomes and at the same time, the tensile strength of the structure increases (Uysal R., 2019).

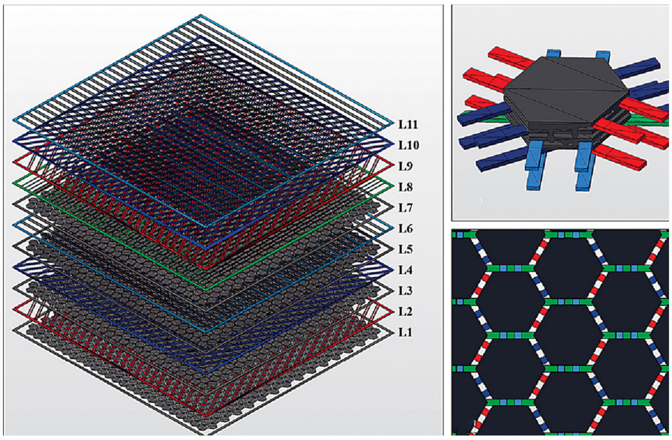

Figure 4.8. Illustration of textile-like surface in Netfabb
Source: Uysal R., 2019

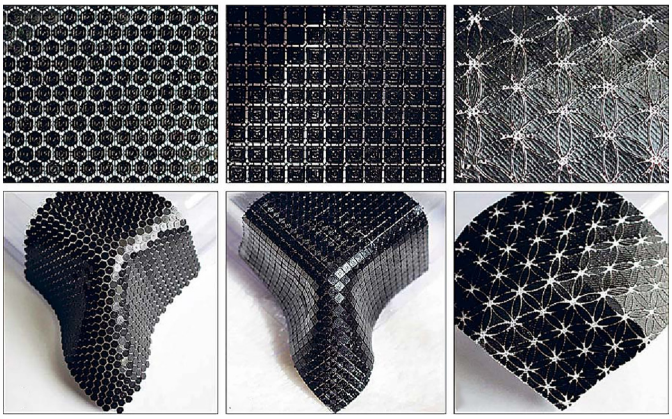

Figure 4.9.Illustration of different repeating patternsSource: Uysal R., 2019

By using a new printing method, various repeating patterns were created for the surface of textile like structures. Furthermore, different effects on the properties of textile-like surfaces were documented. Secondly, the surface of textile-like structures was modified with colours in order to meet the design specific requirements of a textile. In the final step, the printing method was used to print a garment (Uysal R., 2019).

Future work will include the determination of mechanical properties such as tensile strength due to the differences in the number of connecting strands, the orientation of connecting strands, printing speed and the value of Extrusion Multiplier (EM) (Uysal R., 2019).

This experiment showed that it is possible to print multi-material textile-like structures by using the FDM technology. An important aspect of this work was to ensure the wearing comfort of textile-like surfaces. These properties could be ensured by the flexible and elastic printing material LAY-FOMM 40. According to the manufacturer, LAY-FOMM 40 is harmless and food-safe]; therefore, four layers of LAY-FOMM 40 were printed on each model to serve as a skin contact surface. Basically, it is a printed layer of an inner lining, which is also incorporated in conventional clothing. With manual intervention during the printing process on the Z-height of a layer, special effects could be achieved (Uysal R., 2019).

On the one hand, special joining techniques such as ultrasound could be used, whereas on the other hand, 3D printed connections could be developed, which connect textile-like surfaces without a further need for tools (Uysal R., 2019).

Further developments will focus on improving the printing method and lead to further applications for the textile industry. The results of this study are showing the possibilities of 3D printed textiles (Figure 4.10), and serve as an inspiration for other researchers and designers to design garments by using the 3D printing technology (Uysal R., 2019).

Figure 4.10.3D printed glove
Source: Uysal R., 2019

4.5 3D PRINTED FABRIC: Techniques for Design and 3D Weaving Programmable Textiles

Fabric has been one of the promising materials used to create soft objects and presents interesting properties for the fabrication of everyday interactive objects. It adds important properties, such as stretchability, breathability, and flexibility, to a solid object, which are difficult to achieve using rigid materials (e.g., ABS, PLA). Inspired by the use of fabric, researchers and artists have attempted to create 3D printable textiles and clothing through the assembly of small 3D printed pieces, similar to chainmail (Takahashi H., 2019).

Methodology

A new 3D printing technique is presented that can fabricate a soft textile using a conventional FDM 3D printer and a rigid material with the application and extension of the 3D printed hair technique, adjusting the standard movement of a printer, and lengthening tiny bits of extruded materials (i.e., pulling the melted material by quickly moving the head away) to achieve a stringing effect (Takahashi H., 2019). By controlling the movement of the nozzle within a row of pillars, a printer head alternately weaves 3D printed fibers using thin pillars. Unlike chainmail and 3D printed flexible sheets, the textile is “woven” which is constructed by warps and wefts. Although a weft-knitted structure can be 3D printed, this type of complex structure requires an expensive printing method such as selective laser sintering or the use of a removable support material (Takahashi H., 2019).

The technique does not print a weft in a layer-by-layer manner, but a curved shape planned using a design tool can retain its original form and remain fixed when printed. The system also has the ability to generate a Gcode from different geometries and selective parameters (Takahashi H., 2019).

3D Printing Parameters and Control Techniques Gcode is a series of commands used to control printer hardware mechanisms, e.g., the header movement, amount of extrusion, and temperature, which affect the shaping of an object. Researchers have used Gcode to control 3D printers, exploring new expressions rather than accumulating an object layer by layer. 3D Printed hair fabricates fine fibers by exploiting the stringing phenomenon of molten plastic. WirePrint is a system used to build physical wireframes to reduce the printing time by tweaking Gcode for the header, moving diagonally along the z-axis. By controlling the height of the nozzle and the amount of material extrusion, expressive textures can also be printed using FDM. Dual-color mixing and 3D hatching are used to control the layering of two colored materials when designing the surface of an object (Takahashi H., 2019).

Although stiffness and texture are important characteristics of textiles, they remain a challenge to fabricate using current FDM. Thus, researchers have created deformable objects consisting of microstructures. Meanwhile, textile has become a promising material presenting the possibility of integrating its unique flexible and soft properties when fabricated or embedded into a rigid object (Takahashi H., 2019).

The techniques for 3D printing a programmable textile are achieved with the use of a commercial FDM printer Creality 3D CR-10S3, with the most common 0.4-mm-diameter nozzle and a 300 300 400 mm printing area. Several types of PLA, including Polymaker PolyPlus and PolyMax series, were tested. Although the brands of FDM printers and materials are diverse in the market, the basic settings and steps described herein serve as a baseline of the technique (Takahashi H., 2019).

The structure of a printed textile and the printing order can be seen on Figure 4.11. The textile consists of three parts: a base (can be removed afterward), pillars (in the z-axis), and fibers (in the xy axis). A base supports and upholds the entire structure while adhering it to the bed, similar to a brim and it is critical to print a significantly large base to uphold the pillars and fibers in place. A base does not necessarily need to be thick and can be printed as a thin plate with just a few layers, similar to brim. We currently design the base as a rounded rectangle, printed using two layers with 100% density and printed with the speed of 1,000-mm/min. After the printing, the base is removed manually (Takahashi H., 2019).

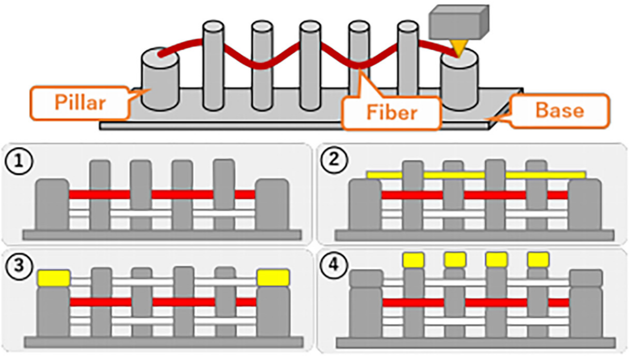

Figure 4.11. Our technique controls the height of the pillars and the order of printing to weave a fiber across the structures.
Source: Takahashi H., 2019

Pillars are equivalent to a warp in which header movements with a fiber extrusion across the pillars correspond to the weft applied in traditional looming.To print an exquisite sheet, the pillars must be printed as thinly as possible. The first setting is the printing speed to 500 mm/min, a slightly low value in order to print it carefully. It is fairly difficult to print a thin and high pillar in the z-direction if printed solely, because the movement of the nozzle may shake and twist the printed pillar as the layer proceeds. However, the printed pillars and woven fibers can support each other in the structure as the fibers cross the pillars and hold them tight (Takahashi H., 2019). As a result it was found that pillar diameters of approximately 0.8 mm can reach a height of more than 300 mm. This pillar is printed with a contour path of a 0.4-mm-diameter cylinder.

Because our 3D printer has a 0.4-mm-diameter nozzle, the extruded material swells slightly around the nozzle. To avoid a collision between the nozzle and pillars while printing, the interval between the pillars must be greater than the distance that allows the nozzle to pass through the spaces between pillars. Approximately 2.4 mm intervals from the center of the pillars were found to be appropriate. It is necessary to print the outermost pillars thicker and stronger, to fix the fibers to the end before the nozzle turns its direction to weave the next layer. Any geometrical shape is available for the outermost pillars as long as it is sufficiently strong to support its structural height. We printed a 3.0 6.0 mm rectangle to build the outermost pillar in a 0.2 mm layer height (Takahashi H., 2019).

To weave fibers that are formed by extruded strands, the order of the printing is rather controlled than printing everything in one layer concurrently. To weave a fiber the 3D printed hair technique is applied, which pulls the extruded material by moving the nozzle away. We set the amplitude of the movement of the nozzle to 1.2 mm (from the center of a pillar to the farthest point of the fiber) according to the pillar interval. The flow rate is the most significant factor affecting the printing fiber by the amount of material extruded and the printing speed.

When printing a long fiber, the area around the end of the fiber becomes thinner as the fixed amount of material exits in the nozzle channel, resulting in material running out while printing the fibers. Therefore, we set Gcode to extrude an additional amount of material when printing a fiber, by adjusting the extrusion amount (E value) (Takahashi H., 2019).

Design space for 3D printing textiles

A variety of parameters and their ranges associated with the printing process and their effects on the characteristics of printed textiles are listed below: (Figure 4.12).

- Length, Height, and Curvature - The maximum length and the height of a fiber is constrained by the size of the bed.
- Density - The density of printed fabric can be controlled in two ways: the interval between pillars, and the vertical density between horizontal fibers.
- Adhesion - Extruded molten plastic quickly cools down and solidifies in mid-air, becoming less adhesive to existing structures.
- Material - Users can integrate the material properties such as the color, flexibility, and conductivity.
- Pattern - By controlling the movement of the nozzle, our technique can create various patterns on a textile surface.

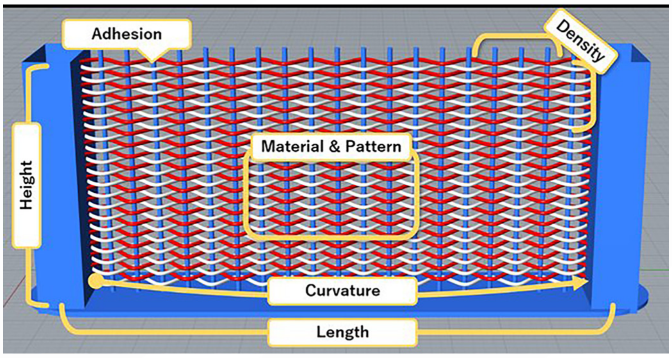

Figure 4.12. Design parameters
Source: Takahashi H., 2019

Design tool for programmable textile

A system that enables users to design textiles by exploring a number of parameters exporting them as a Gcode, was implemented on Rhinoceros and Grasshopper7, which is a visual programming language used to manipulate 3D geometries. The technique presents a wide range of design spaces (Figure 4.13). Therefore the system was extended to several different plugins (Takahashi H., 2019).

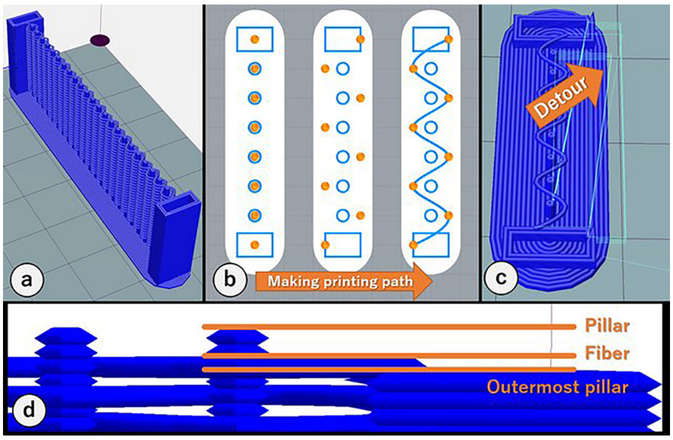

Figure 4.13. Generating a printing path for a textile: (a) Gcode preview. (b) the system generating a path for printing fiber by interpolating the points obtained from the positions of the pillars. (c) To avoid colliding the nozzle with the printed structure, a path for creating a detour is added. (d) The heights of the inner pillars, the outermost pillar, and the fiber are also controlled to avoid a collision Source: Takahashi H., 2019

Programmable Structures

Several types of design plugins are introduced as independent systems that share the same configuration and can be integrated with each other.

Straight Sheet

The simplest system is applied to control the design parameters of the simplest textile. All parameters are controlled by sliders or toggle buttons on Grasshopper. This process operates as the basis of constructing a sheet of fabric for a more advanced feature design. If users employ two types of material, the system builds a prime tower to wipe off the oozing material, and accordingly modifies Gcode based on the nozzle interval (Takahashi H., 2019).

Curvature Sheets and 3D Solid Integration

Grasshopper scripts can import a 3D geometry from Rhinoceros, such as freely drawn lines and the contour of a square. In so doing, users can set the information regarding the shape of the textile. The system obtains a curve drawn in Rhinoceros and generates a curved textile along with imported lines. Similarly, a 3D solid mesh can also be imported into the system as a 3D object component. The system interprets an imported solid as a type of pillar and thus connects the edges of the fibers using a component that calculates the position of the closest edges from the endpoints of the fiber (Takahashi H., 2019).

Patterns with a Binary Image

Our system also enables users to import a 2D image to populate a wide range of new weaving patterns. The system first converts the image into binary images using thresholding, and extracts the value of the black pixels using a grid. The grid is then divided by the interval of the pillars, and Gcode is generated to move the nozzle back and forth (Takahashi H., 2019).Several tests were made in order to assess some important properties of a textile - strength and flexibility. It was found that this printing technique gives high strength and flexibility to the printed textile (Takahashi H., 2019).

A new 3D printing technique for textile fabrication was presented, using a consumer-grade FDM 3D printer. Given a variety of parameter choices, the technique enables weaving a thin fiber across a series of pillars within the design space of the fabricated textile.A system that enables end users to design various textiles (Figure 4.14) by exploring different parameters was introduced. Exemplary applications demonstrate how it can be used in a real-world fabrication, allowing users to introduce thin threads as a new design medium for their 3D models. The proposed technique will expand the application domain of 3D printing, opening a new door for users to recast the use of printers in everyday design, not only for rigid objects but also for objects with soft textiles.

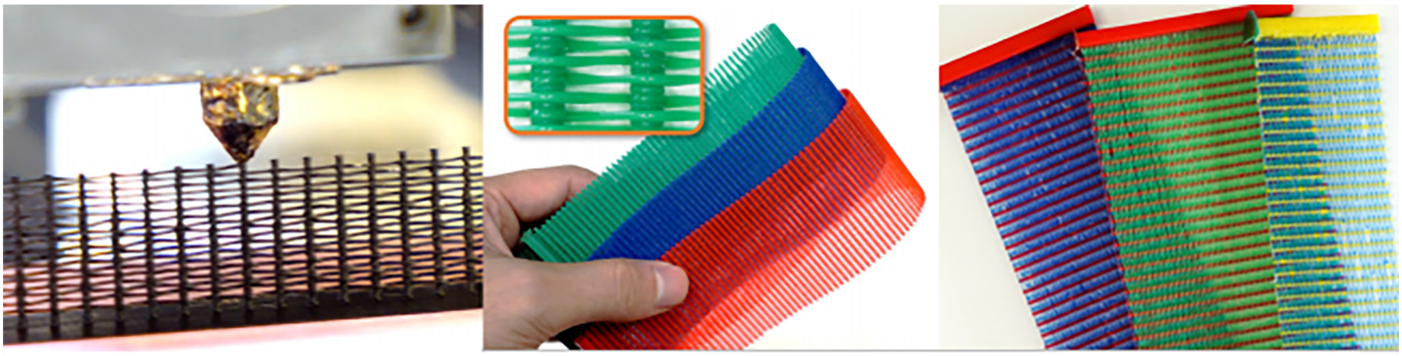

Figure 4.14. 3D printed fabric
Source: Source: Takahashi H., 2019

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CHAPTER V.

DESIGN RULES AND GUIDELINES

5.1 INTRODUCTION

Up to this point all the important information regarding 3D printing technology, textile production, properties, was reviewed in order to give the reader a very systematic representation of the prerequisites when designing for fashion. The benchmarking and study cases are helpful when selecting the right material and process. This chapter will take the reader through the different stages of the process that were described in Chap. 1. There are different ways to break down this process flow, depending on your perspective and equipment familiarity.

Based on the review so far, the basic steps in designing 3D printed textiles are almost clear. There are some important aspects and rules that need to be present in the process in order to have a well structured garment.

5.2 GENERAL DESIGN CONSIDERATIONS

Different 3D printing processes have different capabilities and different design limitations which will be reviewed in the following sections (3D Hubs B.V., 2021).

Introducing so far all the needed information about textiles and 3D printing techniques, there are some more considerations as well.

The most important thing to remember while designing for 3D printing is the fact that the digital design will become a physical object. In the digital design environment, there are no laws of physics to adhere to, such as gravity (Robin Brockotter, 2019).

Anything can be “drawn” in 3D on a digital canvas, but not everything can be 3D printed (Robin Brockotter, 2019).

Each 3D printing process has its own limitations. Here are the most important design considerations that apply to all of them.

5.2.1 Overhangs

Every 3D printing process builds parts layer-by-layer. Material cannot be deposited onto thin air, so every layer must be printed over some underline material (Robin Brockotter, n.a).

Overhangs are areas of the model that need to be supperted. However there is a limit on the angle every printer can produce without the need of support material. For example, for FDM and SLA this angle is approximately 45 degrees.

The best case scenario is to avoid support by limiting the overhangs of a model, because as layers printed over support usually have a rougher surface finish.

Figure 5.1. The effect of increasing angle on overhang quality for FDM printing
Source: www..3dhubs.com

5.2.2 Wall thickness

The second thing to keep in mind when designing a part to be 3D printed is wall thickness. Every 3D printing process can produce accurately features that are thin up to a certain point (Robin Brockotter, 2019).

It is helpful to always add thickness to your models. Walls with thickness greater than 0.8 mm can be printed successfully with all processes.

5.2.3 Warping

Something that is often easily overlooked while designing a 3D model is the fact that the materials used for 3D printing undertake physical change: they are melted, sintered or scanned with a laser and solidified (Robin Brockotter, 2019). The heating and cooling of material can cause the parts to warp while printing.

Warping is typical for flat and large surfaces and can be avoided by using correct machine calibration and having adequate surface adhesion between the part and the print bed.

5.2.4 Level of detail

When a 3D model is crated with intricate details, it is important to keep in mind what is the minimum feature size each 3D printing process can produce (Robin Brockotter, 2019). The minimum level of detail is connected to the capabilities and mechanics of each 3D printing process and to the selected layer height.

Figure 5.2. Marvin printed in 200 microns FDM, 100 microns FDM, SLA and Material Jetting (from left to right)
Source: www..3dhubs.com

The process and materials used will have an impact on the speed and cost of the print, so determining whether smaller details are critical to themodel is an important design decision (Robin Brockotter, 2019).

Of course, there are specific design considerations for the generic 3D printing process that must be followed. They are summarized in Table 5.1.

5.3 STEPS FOR 3D PRINTING OF GARMENTS

In general there are several steps that are mandatory in 3D printing textiles, whether that be in fashion or product design. However, one thing is constant through all design disciplines and that is the starting point, the concept or brief. How we get to the end of that process could be via a number of paths but it increasingly involves not only more that one person, but more than one discipline.

5.3.1 Step 1: Conceptualization

The first step in any product development process is to come up with an idea for how the product will look and function. Conceptualization can take many forms, from textual and narrative descriptions to sketches and representative models (Figure 5.3. and 5.4).If additive manufacturing is to be used, the product description must be in a digital form that allows a physical model to be made. It may be that AM technology will be used to prototype and not build the final product, but in either case, there are many stages in a product development process where digital models are required (Chan.I,2020).

DESIGN RULES FOR 3D PRINTING

3D HUBS

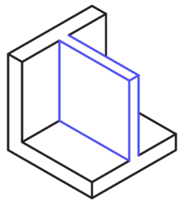
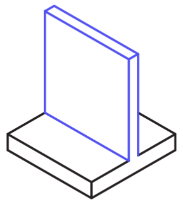
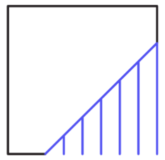
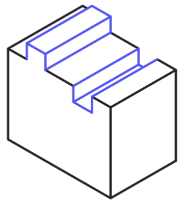
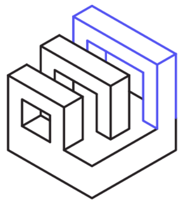
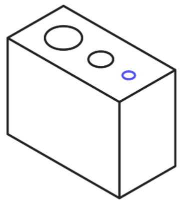
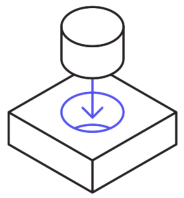
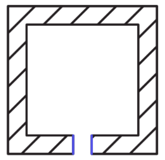
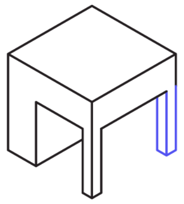
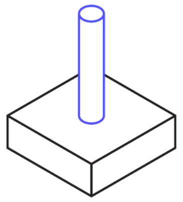
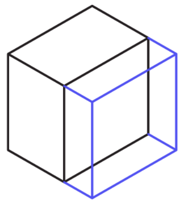
	Supported walls	**Unsupported walls**	**Support & overhangs**	**Embossed & engraved details**	**Horizontal bridges**	**Holes**	**Connecting /moving parts**	**Escape holes**	**Minimum features**	**Pin diameter**	**Tolerance**
	Walls that are connected to the rest of the print on at least two sides.	Unsupported walls are connected to the rest of the print on less than two sides.	The maximum angle a wall can be printed at without requiring support.	Features on the model that are raised or recessed below the model surface.	The span a technology can print without the need for support.	The minimum diameter a technology can successfully print a hole.	The recommended clearance between two moving or connecting parts.	The minimum diameter of escape holes to allow for the removal of build material.	The recommended minimum size of a feature to ensure it will not fail to print.	The minimum diameter a pin can be printed at.	The expected tolerance (dimensional accuracy) of a specific technology.
											
Fused deposition modeling	0.8 mm	0.8 mm	45°	0.6 mm wide & 2 mm high	10 mm	Ø2 mm	0.5 mm		2 mm	3 mm	±0.5% (lower limit ±0.5 mm)
Stereo-lithography	0.5 mm	1 mm	support always required	0.4 mm wide & high		Ø0.5 mm	0.5 mm	4 mm	0.2 mm	0.5 mm	±0.5% (lower limit ±0.15 mm)
Selective laser sintering	0.7 mm			1 mm wide & high		Ø1.5 mm	0.3 mm for moving parts & 0.1 mm for connections	5 mm	0.8 mm	0.8 mm	±0.3% (lower limit ±0.3 mm)
Material jetting	1 mm	1 mm	support always required	0.5 mm wide & high		Ø0.5 mm	0.2 mm		0.5 mm	0.5 mm	±0.1 mm
Binder jetting	2 mm	3 mm		0.5 mm wide & high		Ø1.5 mm		5 mm	2 mm	2 mm	±0.2 mm for metal & ±0.3 mm for sand
Direct metal Laser sintering	0.4 mm	0.5 mm	support always required	0.1 mm wide & high	2 mm	Ø1.5 mm		5 mm	0.6 mm	1 mm	±0.1 mm

Table 5.1. Design rules for 3D printig Source:www.3dhubs.com

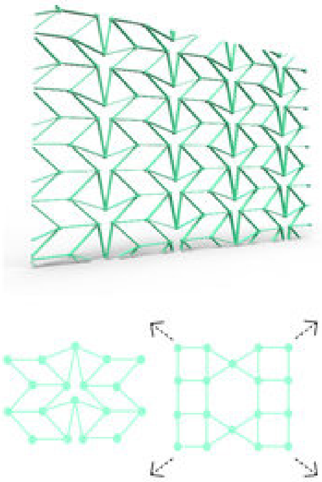


Figure 5.3. Textile pattern
Source: www.mariale.design/loom

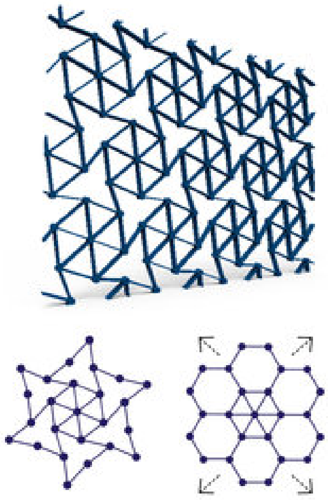


Figure 5.4. Textile pattern
Source: www.mariale.design/loom

5.3.2 Step 2: Data capturing

Sizing of the 3D printed garments can be controlled easily during the design phase. Designers could produce the 3D CAD model and specify or modify the dimensions according to the individual customers using the CAD modelling software. Besides comfort, another important requirement of 3D printed garments is fit (Figure 5.5). To produce perfectly tailored garments that are body-fitting, non-contact 3D body scanning technology can be adopted (Chan.I,2020). Using this technology, body size can be captured accurately and the designer can perform digital design directly on the virtual body contour using CAD software (Figure 5.5).

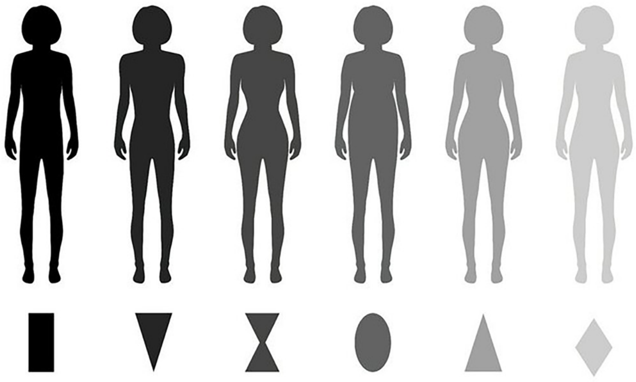


Figure 5.5. Adaptation of body shape and body change
Source: www.mariale.design/loom

Furthermore, the virtual 3D design serves as a platform for direct customer review and fast customisation according to requirements of the customers (Yap Y.L., 2014).

Figure 5.6 Sketches and composition
Source: www.mariale.design/loom

5.3.3 Step 3: Design and modeling tools

Some examples like Solidworks, AutoCAD, PTC Creo and Rhinoceros (Rhino 3D), are commercial CAD software used in the field of engineering, architecture, product design and industrial design. Other available software is listed in table 5.3. There is a difference in the way of modeling with each one - Solidworks is a hybrid solid and surface modeller while Rhino 3D uses non-uniform rational B-spline (NURBS) in surface modelling. As Rhino 3D makes it easier to work with complex curved surfaces as compared to Solidworks, it is more widely used in 3D design modelling of fashion products where the design involves a lot of curved surfaces (Yap Y.L., 2014).

Parametric design processes like computational algorithms are a new design tool in the application of product design. Instead of sketching or building a specific 3D model in the CAD software using primitive shapes, the algorithmic modelling tools use codes made up of interdependent variables or relations (Yap Y.L., 2014). As the computational codes are responsive to changes in specific variables and physical inputs, changing one or more of the parameters generates alternative forms and hence achieves unique individualised design and mass customisation (Yap Y.L., 2014).

Generative parametric design tools are extremely valuable for providing fast customisation to people who are not familiar with CAD modelling. These tools are also very convenient for design of 3D printed garments as one source code is able to generate endless forms of design based on an individual's preference. At the same time, the parametric design tools are able to calculate and check the generated forms' functionality and printability, based on the constraints and boundary set by the designer (Yap Y.L., 2014)

The CAD skills are essential for 3D printing and ,as mentioned in Chapter III, the differences between a fashion designer's knowledge and a product designer's knowledge are different. It was found that both lack some skills but the most important one was the ability to use 3D CAD software which the fashion designer needs to learn. Knowing how to create any structure in 3D CAD software is such an advantage. Although product designers should gain the missing knowledge in textiles and vice versa the best outcome will be when designing a 3D printed garment to have both fashion and product designers work together and create s structure both suitable for the body and realistic to 3D print.

5.3.4 Step 4: Export to STL

Nearly every AM technology uses the STL file format. The term STL was derived from Stereolithography, which was the first commercial AM technology from 3D Systems in the 1990s (Gibson, 2015). STL is a simple way of describing a CAD model in terms of its geometry alone. It works by removing any construction data, modeling history, etc., and approximating the surfaces of the model with a series of triangular facets. The minimum size of these triangles can be set within most CAD software and the objective is to ensure the models created do not show any obvious triangles on the surface (Gibson, 2015).

STL files are an unordered collection of triangle vertices and surface normal vectors. As such, an STL file has no units, color, material, or other feature information. These limitations of an STL file have led to the recent adoption of a new "AMF" file format (Gibson, 2015). This format is now an international ASTM/ISO standard format which extends the STL format to include dimensions, color, material, and many other useful features (Gibson, 2015).

Since STL is essentially a surface description, the corresponding triangles in the files must be pointing in the correct direction; in other words, the surface normal vector associated with the triangle must indicate which side of the triangle is outside vs. inside the part. The cross-section that corresponds to the part layers of a region near an inverted normal vector may therefore be the inversion of what is desired (Gibson, 2015).

SOFTWARE	PROVIDER (WEBSITE)	CHARACTERISTICS	MAIN APPLICATIONS
MAYA	Autodesk(http//www.autodesk.com/products/maya/).	Modeling of the polygonal method Functions of modeling rendering and simulation.	Modeling of the polygonal method Functions of modeling rendering and simulation.
Rihino	Rovert McNeel & Associates (http://www.Rihino3d.com).	NURBS method 3D modeling of most advanced mathematical expression method. Suitable for precise and acurate design work.	Industrial design, architectural design, engineering, mold design, jewerly design, handlcraft design.
Sketchup	Trimble Navigation (http://www.sketchup.com/).	Sharing platform,providing warehouses,and enabling a user to upload. Simple and easy for 3D modeling.	Architecture,landscape,interior design,product design,online games.
AutoCAD	Autodesk (http://www.autodesk.com/).	Top leader in 2D-based software. Several inconvenlent aspect in 3D modeling.	Architecture, electricity, mechanical engineering, civil engineering.
Zbrush	Pixologic (http://pixologic.com/).	Modeling of the polygonal method. Having a tool of sculpting brush.	Movies, animation, online games, fine art works,design.
3Ds MAX	Autodesk (http://www,autodesk.com/products/3ds-max/overview)	Biggest numbers of users in the world. Compatible with several plug-ins.	Architecture,online games, grapics
Other (e.g., 123D Design, Blender, NaroCAD)	Autodesk, Blender Foundation.	Simple function and intulitive UI. Easy marking of simple objects.	Design

Table 5.3.Available CAD software

Additionally, complex and highly discontinuous geometry may result in triangle vertices that do not align correctly. This may result in gaps in the surface. Various AM technologies may react to these problems in different ways. Some machines may process the STL data in such a way that the gaps are bridged. This bridge may not represent the desired surface, however, and it may be possible that additional, unwanted material may be included in the part (Gibson, 2015).

While most errors can be detected and rectified automatically, there may also be a requirement for manual intervention. Software should therefore highlight the problem, indicating what is thought to be inverted triangles for instance. Since geometries can become very complex, it may be difficult for the software to establish whether the result is in fact an error or something that was part of the original design intent (Gibson, 2015).

5.3.5 Step 5: Slicing software

It is sometimes challenging for a 3D printer to directly read a file made from 3D modeling software. Therefore, it needs to convert STL data made from 3D modeling software into the path data sliced into layers, where each layer is as thick as a one-time movement of the printer head. This path data is called G-Code and the software converting into G-Code is called 'slicing program'. Numerous slicer software are available in the software market (e.g., CURA, KISSlicer, Slic3r, Make Ware) (Kwon Y.M., 2017).

5.3.6 Step 6: Machine Setup

All AM machines have a few setup parameters that are particular to that machine or handle. A few machines are planned to run with many specific materials and grant the client many alternatives for layer thickness or construct parameters. These sorts of machines will have exceptionally few setup changes to form from construct to construct. Other machines are outlined to run with a variety of materials and may moreover have a few parameters that require optimization to suit the sort of portion that's to be built, or permit parts to be built faster but with poorer quality. Such machines can have various setup options accessible. It is common within the more complex cases to have default settings or save files from already characterized setups to assist speed up the machine setup and to prevent mistakes. Ordinarily, an inaccurate setup strategy will result in a part being built but its geometry may be unsatisfactory (Gibson, 2015).

In addition to setting up machine software parameters, most machines must be physically prepared for a build (Gibson,2015). The operator has to make sure that sufficient build material is loaded into the machine to complete the build. For machines which use powder, the powder is often sifted and subsequently loaded and leveled in the machine as part of the setup operation. For machines that use a liquid material, the tank where it is poured needs to be cleaned up after every usage of the machine. For processes which utilize a build plate, the plate must be inserted and leveled with respect to the machine axes. Some of these machine setup operations are automated as part of the start-up of a build, but for most machines these operations are done manually by a trained operator (Gibson, 2015).

5.3.7 Step 7: Post-processing

Ideally, the output from the AM machine should be ready for use with minimal manual intervention. While sometimes parts will require a significant amount of post-processing before they are ready for use. In all cases, the part must be either separated from a build platform on which the part was produced or removed from excess build material surrounding the part (Yap Y.L., 2014).

Some AM processes use additional material other than that used to make the part itself (secondary support materials)(Figure 5.5). Different AM parts have different cleanup requirements and this stage can be considered as the initial part of the post-processing stage (Yap Y.L., 2014).

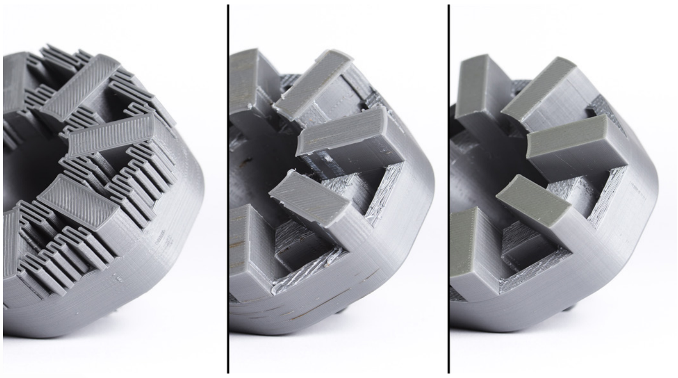


Figure 5.7. Support structures removal
Source: www.3dhubs.com

Product aesthetics is essential to influence consumers' perception on the value of the product. It is therefore significant to ensure the 3D printed fashion products are relevant to the fashion products fabricated by traditional manufacturing techniques. Though 3D printed fashion products nowadays can be built using various types of material and the resolution of many 3D printers has been vastly improved, the visual quality of the majority of the printed products is not yet satisfactory. This is mainly attributed to the staircase effects resulting from the layer by- layer method of building as well as the unattractive mono colours of the raw materials in many AM processes, such as SLS, SLM and SLA (Gibson, 2015). Nevertheless, there are developments in reducing obvious print lines resulting from layer-by-layer manufacturing (Yap Y.L., 2014).

Other common finishing techniques are grinding, sanding and polishing to achieve an appealing surface finish and texture for metal and polymer parts (Figure 5.7). Generally, manual polishing that is both time consuming and expensive, has to be performed to produce high surface quality for fashion products with an intricate and complex surface as most of the surface cannot be polished by mechanical means (Yap Y.L., 2014).

Upon polishing, electroplating or anodising can be carried out to further enhance aesthetics and durability (Yap Y.L., 2014).

Spray painting and dyeing are finishing techniques to apply colours to the 3D printed products. These processes can produce a wide range of finishes and colours and are applicable to almost all materials (Yap Y.L., 2014).

Figure 5.8. Part aesthetics
Source: www.3dhubs.com

5.3.8 Step 8: Additional design procedures

Most of the commercial 3D printers have a relatively small build volume, and it is challenging to produce the whole apparel within a single build process. It is therefore essential to segment the design into smaller pieces in order to fit into the allowable build size of the selected 3D printer. The small pieces need to be assembled together to form the final products, as a result, additional joining mechanisms have to be incorporated into the design before printing (Yap Y.L., 2014). In addition to printability, material consumption, surface finish, build time and overall aesthetic must be taken into account during the modification of the CAD design.

Segmentation of the design into smaller pieces for printing is one of the modifications that can be performed. This helps to print with the least support materials and fastest speed. After segmentation, these small sections have to be assembled together to form the final fashion product. Generally, it is convenient to bond the small sections together using suitable adhesives (Yap Y.L., 2014).

Special physical joining mechanisms can also be used to replace adhesive. Joints like helical springs and cufflink-like objects are useful to join sections. Helical springs coiled around the thin struts are able to provide firm yet flexible joints. The cufflink-like objects could serve as detachable joints like traditional buttons or snap buttons that may be easily removed or installed (Yap Y.L., 2014).

As an alternative to dividing the design to fit the build size of the 3D printers, the designer can also embed flexible joining mechanisms within the design to allow folding of the design into a smaller size. One example that demonstrates the feasibility of this idea is the Nervous System's Kinematics that allows the design to be folded into a more compressed form so that the design fits into a 3D printer. The design is composed of multiple small components that interlock by accurately spaced hinge joints, enabling the design to drape and move like real fabric (Yap Y.L., 2014).

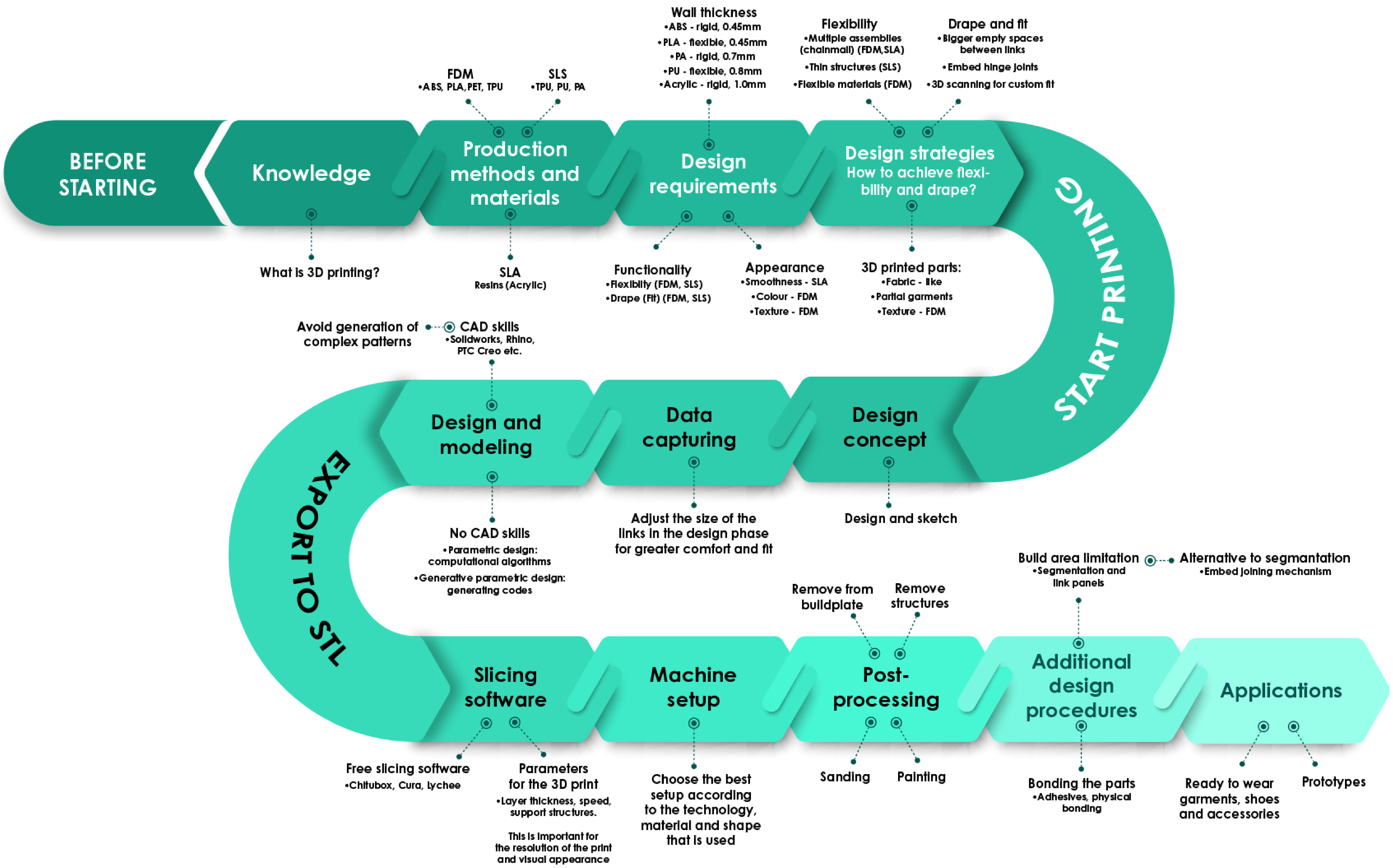
5.3.9 Step 9: Application

Apparel manufacturers, retailers and designers have been using 3D-printers for different functions - to create prototypes for testing, for customization of the products, creating of artistic pieces and spares. Popular are becoming 3D-printed bikinis, shoes, dresses , where normally using a combination of printing from solid soft material and creating flexible structures are used.

5.4 CONCLUSION

While there are a variety of trade publications that discuss how general 3DP methods are used by designers and companies in the fashion industry, there is a lack of scholarly information about 3D printing for the fashion industry. In this chapter design considerations and guidelines were reviewed in order to provide a more systemized information of how to design for fashion (Table 5.4). However, it is not that simple as it sounds and the specific rules need to be followed when designing for 3D printing.

A ROADMAP OF THE ENTIRE 3D PRINTING PROCESS OF GARMENTS



BEFORE STARTING

Knowledge

What is 3D printing?

Production methods and materials

FDM
- ABS, PLA, PET, TPU

SLS
- TPU, PU, PA

SLA
Resins (Acrylic)

Design requirements

Wall thickness
- ABS - rigid, 0.45mm
- PLA - flexible, 0.45mm
- PA - rigid, 0.7mm
- PU - flexible, 0.8mm
- Acrylic - rigid, 1.0mm

Functionality
- Flexiblity (FDM, SLS)
- Drape (Fit) (FDM, SLS)

Appearance
- Smoothness - SLA
- Colour - FDM
- Texture - FDM

Design strategies
How to achieve flexibility and drape?

Flexibility
- Multiple assemblies (chainmail) (FDM,SLA)
- Thin structures (SLS)
- Flexible materials (FDM)

Drape and fit
- Bigger empty spaces between links
- Embed hinge joints
- 3D scanning for custom fit

3D printed parts:
- Fabric - like
- Partial garments
- Texture - FDM

START PRINTING

Design concept

Design and sketch

Data capturing

Adjust the size of the links in the design phase for greater comfort and fit

Design and modeling

CAD skills
- Solidworks, Rhino, PTC Creo etc.

Avoid generation of complex patterns

No CAD skills
- Parametric design: computational algorithms
- Generative parametric design: generating codes

EXPORT TO STL

Slicing software

Free slicing software
- Chitubox, Cura, lychee

Parameters for the 3D print
- Layer thickness, speed, support structures.

This is important for the resolution of the print and visual appearance

Machine setup

Choose the best setup according to the technology, material and shape that is used

Post-processing

Remove from buildplate

Remove structures

Sanding

Painting

Additional design procedures

Build area limitation
- Segmentation and link panels

Alternative to segmantation
- Embed joining mechanism

Bonding the parts
- Adhesives, physical bonding

Applications

Ready to wear garments, shoes and accessories

Prototypes

Table 5.4.

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CHAPTER VI.

CONCLUSIONS, INDUSTRIAL IMPLICATIONS AND FUTURE RESEARCH

Since three-dimensional printing was first introduced it has been widely used in many manufacturing industries from medicine to transportation, and has even slowly become popular in the fashion industry and even create garments at home with a desktop 3D printer. 3D printing is a way of manufacture where material is laid down layer by layer to create 3D objects. These objects are created from a digital file containing three-dimensional data extruded by printer, which can employ a wide range of materials and techniques (Hoffman T ,2015).

Most of the current commercial available 3D printers have limited printing areas. For printing 3D garments FDM, SLS and SLA are often used due to the comfortability of the printed items they can print. Light weight polymers or polymer composites are the main materials used as printing materials allowing flexibility of the printed items. It is able to build objects by layers to eliminate unnecessary production of small pieces, but instead 3D object printing can be produced in one setting, cut time not only depends on the production, but also the assembly. This leads to the understanding that if fewer pieces need to be made, it allows to reduce the amount of waste. This would be very useful to the garment manufacture industry as fabric waste is one of the biggest issues while mass manufacturing brands to avoid any considerations of reducing seam allowances, pattern sizing, changing pattern lay plans and many more. 50% of the final cost of a garment is made up from a cost of the material that has been used in production, therefore, if it is possible to eliminate the cutting process altogether, it will make zero material waste possible.

Not only is it good for producing prototypes or samples in small scale, but also in mass manufacturing, because of the size, colour and shape of the generated 3D object can be easily changed in a computer without adding additional cost.

Because of the process of 3D printing, it allows to avoid disadvantages of conventional manufacturing, one of them being the lack of flexibility. It can be noted that because of the whole unit is built independently, it requires to get changed easily to accommodate the enhancements or change of fashion. Moreover, the manufacturing preparation process itself is simple because it needs fewer stages (D'Aveni R, 2015).

The research proved that it is possible to create garments that are able to feature 3D printing leading to many potential impacts (Valtas A.,2016). It is noted that this is more at the conceptual stage rather than at an actual stage of manufacture that can completely overtake the manufacturing that is known today. By carrying out the research several points in the requirements for designing 3D printed garments were made based on literature review and comparison of the conventional and unconventional methods in production. One of the most important requirements before even starting designing is the knowledge in AM processes, traditional textiles, textile properties, CAD modeling. The next very important step is to choose the right technology and materials and then make decisions about the structure to be printed according to the desired properties of the 3D printed textile. Although in this paper a complete roadmap and guidelines for printing in the fashion industry was introduced, it does not seem that simple. The aim was to give to those who want to design garments a simplified guide with instructions and information.

Future research in 3D garment printing should look more at the development of novel filament materials, relationship between pattern/element selection and flexibility of the printed garment, etc. (Valtas A.,2016).

3D printing in fashion is still in its early stage and if it were to be soon seen on the high-street, it would probably be introduced through high-end brands that create their collections not only to sell the product, but use it as a marketing tool. A 3D printed garment or part of a garment that is created with 3D printers has not been widely manufactured in the fashion industry. The access to 3D printing technology still involves high investment costs and time during the production of the 3D elements and further research and developments are required.

CHAPTER VI.REFERENCES

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