3D Printing Technology for Textiles and Fashion

Tanvir Mahady Dip[a], Ayesha Siddika Emu[a], Md Nafiul Hassan Nafiz[a], Puja Kundu[a], Hasnatur Rahman Rakhi[a], Abdullah Sayam[a], Md Akhtarujjman[a], Mohammad Shoaib[a], Md Shakil Ahmed[a], Swimi Tabassum Ushno[a], Abdullah Ibn Asheque[a], Enamul Hasnat[a], Mohammad Abbas Uddin[a] and Abu Sadat Muhammad Sayem[b]

[a]Bangladesh University of Textiles, Dhaka 1208, Bangladesh

[b] Manchester Fashion Institute, Manchester Metropolitan University, Manchester, UK

Corresponding Author email: asm.sayem@mmu.ac.uk; abbas.shiyak@butex.edu.bd

ORCID: Abu Sadat Muhammad Sayem http://orcid.org/0000-0003-3034-7892

Tanvir Mahady Dip https://orcid.org/0000-0002-3227-2743

Ayesha Siddika Emu https://orcid.org/0000-0001-7147-2142

Md Nafiul Hassan Nafiz https://orcid.org/0000-0001-6891-3728

Puja Kundu https://orcid.org/0000-0001-6296-6327

Hasnatur Rahman Rakhi https://orcid.org/0000-0001-8630-9276

Abdullah Sayam https://orcid.org/0000-0002-3645-9353

Md Akhtarujjman https://orcid.org/0000-0001-6103-4026

Mohammad Shoaib https://orcid.org/0000-0002-5385-8487

Md Shakil Ahmed https://orcid.org/0000-0002-9830-2394

Swimi Tabassum Ushno https://orcid.org/0000-0003-3976-3593

Abdullah Ibn Asheque https://orcid.org/0000-0001-8289-0040

Enamul Hasnat https://orcid.org/0000-0002-7014-5462

Abstract:

3D printing (3DP) is one of the modern approaches in the field of manufacturing. Although this process has been known for a fair amount of time, only the recent developments have revealed its novel and true potential for applications in different manufacturing sectors. Textile, one of the basic human requirements, does more than just fulfilling the fundamental necessity of covering our body. Integrating 3DP technology in textiles has broadened the horizon of the textile world. This review explores the historical background as well as state-of-the-art developments in 3DP related to textiles and fashion. Basic ideas about fundamental textile substrates, various 3DP technologies related to textiles, different printing devices and tools, materials used as print inks, direct printing of 3D objects on various textile substrates, fabrication techniques of 3D printed textile structures, different process parameters and their impacts, tests and standards, benefits and limitations are the contents of the discussions throughout this paper. It also highlights the future aspects concerning the further implementation of 3DP technology in the textile industry. Overall, the paper draws a picture with an intention to ascertain the undeniable promise of 3DP, despite having some drawbacks, to enrich the future of the textile and fashion industry with an aim to motivate future designers and scientists towards further exploration within this field of knowledge.

Keywords: 3D Printing, Textiles, Fashion, Fabrics, Polymer, Software

Contents

1. Introduction:

Over the last few decades, three-dimensional printing (3DP) has gained popularity due to the direct fabrication technique assisted by digital design it employs [1]. The application field is vast including the textile and fashion industry [2] as an alternative to the traditional manufacturing process [3]. The technique involves fabrication in a layer-after layer in different geometrical shapes based on 3D modelling information [4].

The idea of 3DP was introduced in 1980 for the first time [5] by a Japanese inventor Hideo Kodama from the Nagoya Municipal Industrial Research Institute as a rapid prototyping device [6] using photopolymer in UV light [7]. Since then, 3DP has contributed quite heavily to the third industrial revolution, especially after 1984 onward [8]. The stereolithography (SLA) technique was successfully patented by Charles Hall of Central High School in Grand Junction, Colorado in 1986 and the device SLA-1 was commercialised in 1988 [3, 7, 9, 10]. Another technique, the selective laser sintering (SLS) 3DP, was invented by Carl Deckard of the University of Texas at Austin in the same year, with a commercial machine marketed as “Betsy”. Other 3DP techniques, such as laminated object manufacturing (LOM) by Helisys, the fused deposition modelling (FDM) by Stratasys and the solid ground curing (SGC) by Cubital, became available in 1991 [3]. A US patent (nr. 5121329) was issued on the FDM technique for Crump family of Stratasys limited, which has become the most popular 3DP technique today, on the 9th of June 1992 [5, 10]. Among these techniques, SGC was dropped later in 1999 due to its high cost associated with complex manufacturing operation [11]. The historical timeline of early development in 3DP is in the **figure 1** [3, 10]

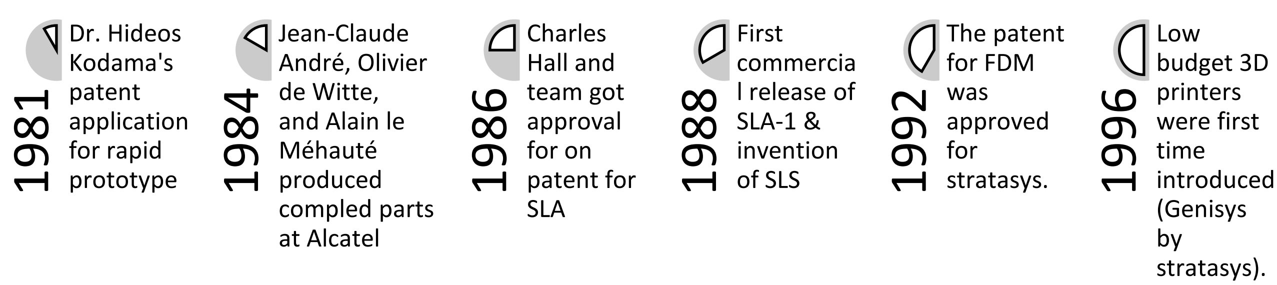


Figure 1. *Timeline for the historical development of different 3DP technology*

The patent details of major additive manufacturing processes are summarised in the **table 1** [5, 11–13]:

Table 1: Patent award timelines of different additive manufacturing techniques

3DP technology	Patent number	Date of award	Years of development
Inkjet printing (IJP)	US patent 2566443	4^{th} September 1951	Early 1950's
Fused deposition modelling (FDM)	US patent 5121329	9^{th} June 1992	1988-1991
Laminated object manufacturing (LOM)	US patent 4752352	21^{st} June 1988	1985-1991
Stereolithography (SLA)	US patent 4575330	11^{th} March 1986	1986-1988
Selective laser sintering (SLS)	Us patent 4863538	5^{th} September 1989	1987-1992
Laser engineered net shaping (LENS)	US patent 6046426	4^{th} April 2000	1997

The major industrial application fields of 3DP are aerospace [14, 15], automotive [16], textile and fashion [3, 7], food [17, 18], healthcare [19, 20], architecture, building, and construction [21], electric and electronic [22–24] [25] as presented in the **figure 2.**

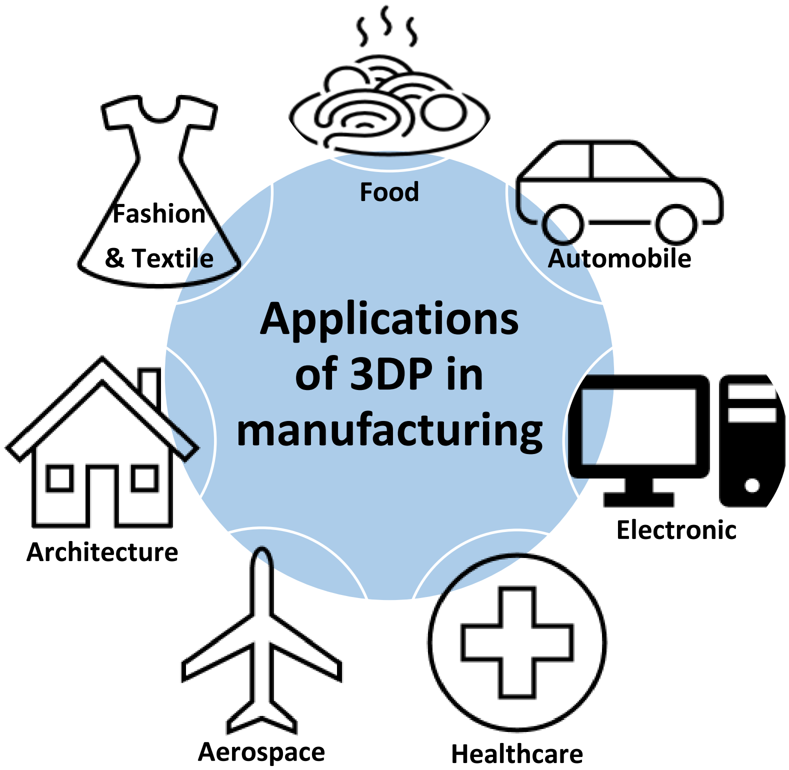


Figure 2. *Industrial applications of 3DP*

Over the last few years, there has been an outburst of hype and concern around 3DP for textiles and fashion [26]. Combining 3DP with traditional textiles like knitted fabrics has been found advantageous [27]. New application areas can be developed with modification and customisation of textiles using 3DP [28]. It is possible to manufacture novel smart textiles by 3DP of functional materials on to textiles [29, 30]. A wide variety of print components such as polymers, resins, ceramic, glass, metal, wax, natural, synthetic fibres, composites, etc., are available to choose from and can be used in a comprehensive range of forms - liquid, solid (as filament or powder) or gas [3]. The concept of printing and attaching conductors, actuators, antennas, and sensors on the textile substrate can be crucial for smart textile application [30, 31].

This review aims to gather latest developments promoting the implementation of 3DP technology in various sections of the textiles and fashion industry. Starting with a brief historical overview, this paper gradually discusses fundamental textile substrates followed by current state-of-the-art 3DP techniques available, which are being implemented in textiles. The design tools, software and the range of printing materials available to be applied for textiles are discussed. Next, it concentrates on recent successes and attempted research works on both 3DP on conventional textile substrates and direct 3D printed textile structures (i.e. yarn, fabric, garment, etc.) imitating the conventional ones. It also encompasses recent advancement in fabricating smart textiles by adjoining functional and novel parts, wearable electronics etc., with textiles through 3DP technologies. The associated advantages and disadvantages of 3DP techniques for textile applications are highlighted. In addition, the effect of various process parameters [32], different test methods and standards to validate final product characteristics are discussed. The paper presents some important points regarding the future development prospects on 3DP's influence over the ever-growing textile industry.

2. Overview of Textile Materials

Textiles are flexible substrates made from a wide variety of different natural, synthetic or composite components in the form of fibres, filaments, yarn or fabric structures [33–35]. However, the concept and application areas of textiles can be broad when the products for technical applications, for example, geo textiles, smart textiles etc., are considered [36–38]. The very basic elements of forming textiles are fibres, which can come from both natural and human-made sources [39]. Fibres are gathered, aligned and twisted to form a continuous strand called yarn [39]. Subsequently, yarns are woven (interlaced) or knitted (interlooped) to make pliable two-dimensional sheet of materials known as fabrics [40]. The fabrics are processed and coloured following mechanical and chemical processes before being cut and sewn to form garments. The **Figure 3** zooms into the different textile structures within a woven shirt.

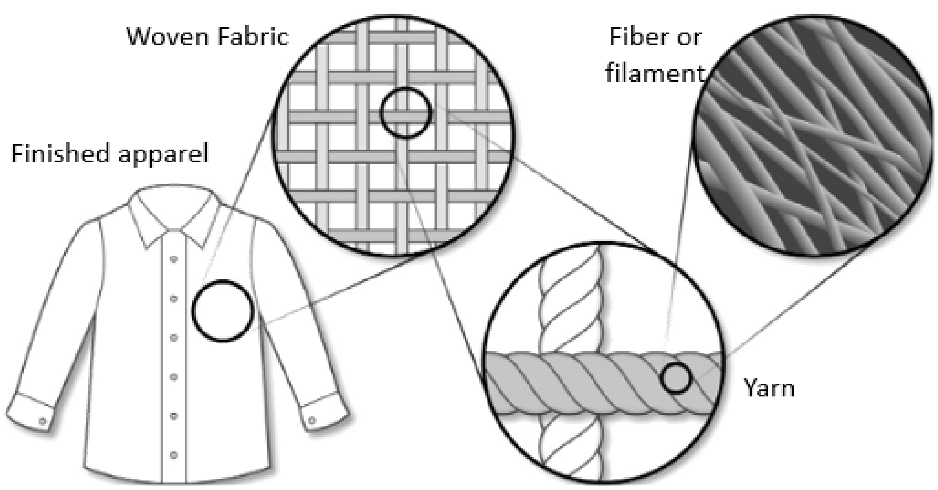
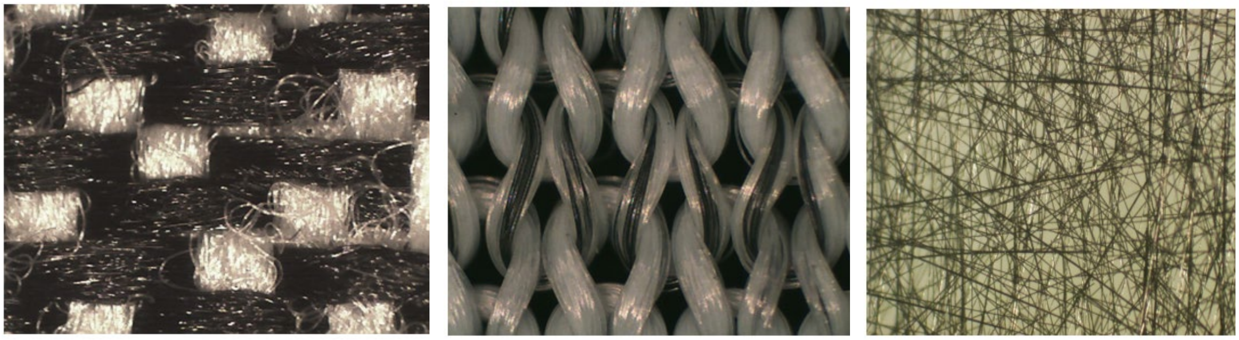


Figure 3. *Macro and micro textile structures within a woven shirt, reused with permission from* [41]*, Copyright © 2017 Elsevier Ltd.*

Key technical steps in textile manufacturing are listed below.

- ***Spinning*** – This process imparts twists into fibres to form a continuous yarn. Depending on the types of yarn to be produced, different methods and machines are used [41].
- ***Fabric manufacturing*** – Yarns are converted into two-dimensional fabrics by either of the techniques called weaving and knitting. In addition, non-woven techniques are also used to produce fabric directly form fibre [42]. All three structures are shown in the **figure 4**. Woven fabrics are constructed via interweaving of two yarn sets called the warp and weft [43], and knitted fabrics are constructed in a row by row manner by continuously interlocking and interlooping of yarns [44, 45]. However, in non-woven fabrics, the materials are bonded together by entangling the fibres or filaments using mechanical, thermal, or chemical-based methods [46, 47]. The latest addition to this field is the 3D printed fabric-like structure [48]. Although it is quite not possible to achieve comparable textile-like properties on 3D printed fabric-like structures, some degrees of breathability and flexibility have been found reproducible [49]. Moreover, the continuous looping structure can be replaced by linkable geometry of AM with required flexibility and drapability [45, 50].
- ***Dyeing/finishing*** - The fabric is coloured by a sequence of dry and wet processes that could involve singeing, desizing, biopolishing, scouring/bleaching, mercerizing, dyeing, heat-set, finishing, compacting etc. A lot of chemicals and water are used in these processes [51].

  Garment making – Garments are made from fabrics through a combination of operations including cutting and sewing [52]. Nowadays, with the advancement of 3DP, complete garments are being made escaping the "cut & sew" process. The 3D parts of a garment are printed in specialised 3D printer and then assembled to make a complete dress [7]. Further details of 3DP garments have been discussed in the 8.3 section of this paper.



a b c

Figure 4. *Microscopic view of the technical construction of a) woven, b) knitted, and c) non-woven fabric, from left to right. Reused with permission from* [46]*, Copyright © 2018 Elsevier Ltd.*

Typical step by step flow with associated operations in textile manufacturing is represented in the **figure 5**.

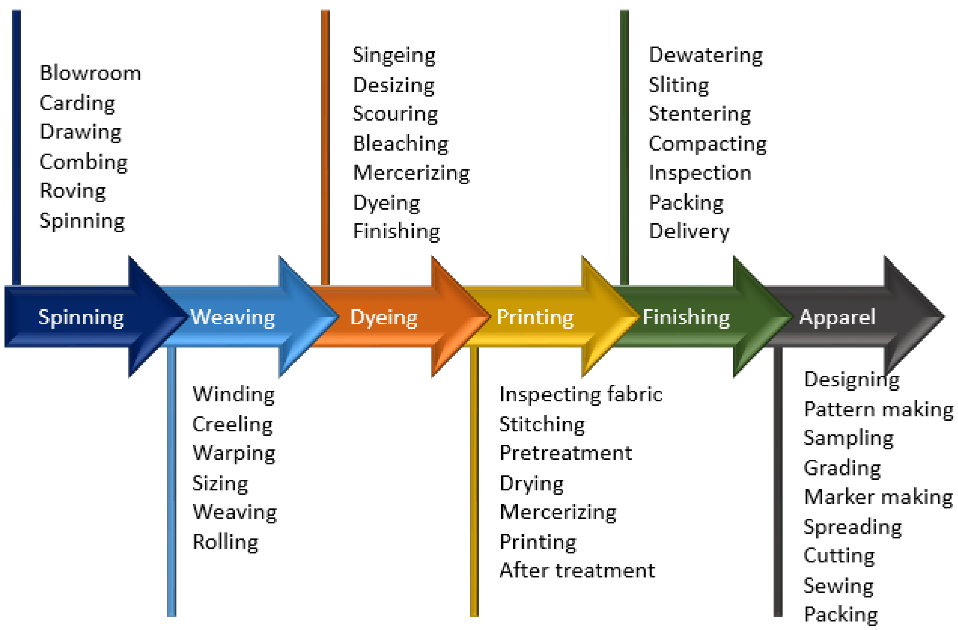


Figure 5. *Textile Manufacturing Processes*

As mentioned earlier, the application area of textiles is vast. The household application includes carpeting, furnishing, bed sheets, curtains, towels, table and chair cover etc. Industrial textiles are manufactured in special design and style to use in non-textile industries where the application includes filter fabric, sound absorption material, conveyer belt, ropes, hoses. Textiles are also used to give strength to composite materials [53]. Other technical textiles fall into the group of agrotech, build tech, geo-tech, meditech, pro-tech, sport-tech, etc. [54, 55]. Another rising area for textiles is the smart textiles with embedded electronics or sensors [56, 57]. The **Figure 6** displays some examples of these areas of application.

Figure 6. *Different application areas of textiles* ***a)*** *Concept of wearable electronic clothing, reused under the Creative Commons Attribution (CC BY) license (http://creativecommons.org/licenses/by/4.0/).* [58]*, Copyright © 2020 MDPI, Basel, Switzerland.* ***b)*** *Pictures of some geotextiles, reused under the terms of the Creative Commons Attribution 3.0 License.* [59]*, Copyright © 2019 IntechOpen* ***c)*** *Application of medical textile, reused with permission from* [60]*, Copyright © 2020 Elsevier Ltd.* ***d)*** *Application of textile in sports, reused with permission from* [61, 62]*, Copyright © 2015 Elsevier Ltd.* ***e)*** *Use of textile in industrial application in the form of conveyer belts and tubular braids, reused under the terms of the Creative Commons Attribution 3.0 License.* [63, 64]*, Copyright © 2017, IntechOpen.*

3. Concept of 3DP

With the intention of making 3D objects as a direct approach, 3DP has become a versatile process in the modern world [65]. Despite its common usage, the term '3DP' can be implied from different perspectives to indicate various aspects. It substantiates multiple concepts, which are denoted as rapid prototyping (RP), additive manufacturing (AM) or solid-freedom technology (SFT) [66].

From the fundamental point of view, 3DP can be referred to as the procedure used to produce three dimensional objects by layering and placing over materials without design molds. This process is an alternative to other subtractive manufacturing technologies that produces the final product by removing excess parts of raw materials through cutting, grinding, corrosion, and melting [67]. It is envisioned that soon 3DP will turn out to be one of the fundamental technologies in industrial manufacturing [68]. It is a process through which an object can be shaped without any supplementary apparatuses and unwanted material wastage [43]. As the material is added layer by layer, 3DP processes are inherently “green” and sustainable. A part is produced using a definite amount of materials without any wastage in a 3DP process [69].

From a simpler perspective, 3DP can be defined as such a kind of production system that spreads out typical printing material, also known as printing ink, into the 3D formation via consecutively depositing components onto a print bed by utilising a standard or custom-made print head [70]. Machines used for AM or 3DP are called 3D printers. The main parts of a general 3D printer include hot end, nozzle, extruder, print bed, cooling fan, build area, etc. [71]. Among various available 3DP techniques, FDM has become a prevalent 3DP technique in prototyping and manufacturing in a multitude of industries. This is because of its simplicity in use, relatively lower cost, environment-friendly features, etc. [72]. A basic arrangement for printing a product by FDM technology has been shown in the **figure 7** to understand the concept of 3DP easily**.** The commands in the CAD file are followed first by the 3D printer for building the foundation of any product. The section 5 later discusses on how CAD data is processed in relevant software system suitable for 3DP. When in action, the printing head of a 3D printer moves along the x–y plane and along the z-axis synchronously to form a complete product layer by layer in vertical direction [73].

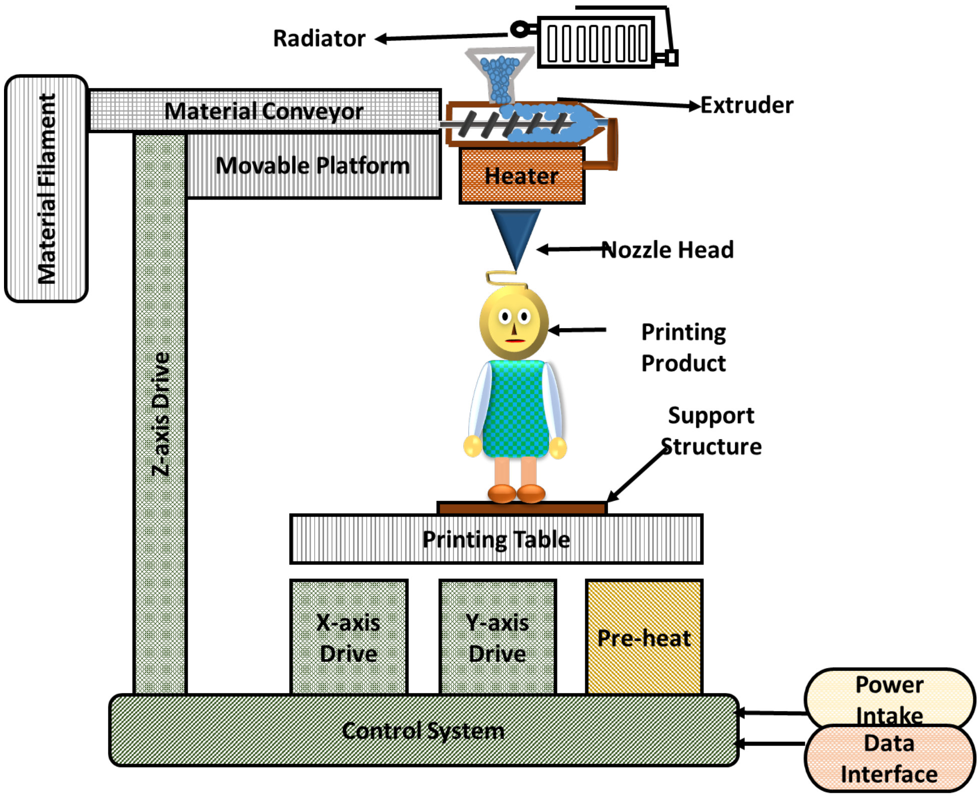


Figure 7. *Schematic diagram of a 3DP device (based on FDM technique) used in 3DP process, Recreated with permission from* [74], *Copyright © 2016, Elsevier B.V.*

The effectual accomplishment of a definite 3DP process demands the involvement of the printing process itself along with modelling, selecting printing materials and methods, and finishing steps to create a complete product [67, 75]. The **Figure 8** shows the workflow of generating the final 3D product from any design concept from a manufacturing perspective.

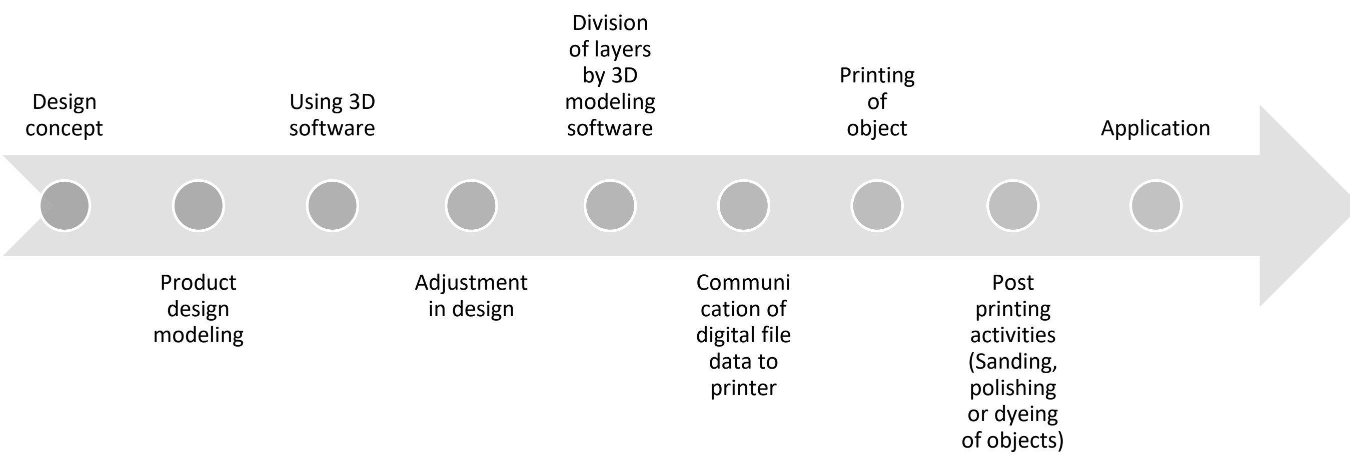


Figure 8. *Typical design and fabrication flowchart of 3DP methods, based on* [3, 43]

3DP process incorporates eight key stages, as presented in the **figure 9** [76]. Required time and human involvement vary depending on factors such as size, height and complexity of the products, use of printing materials and type of 3DP machines [77–79].

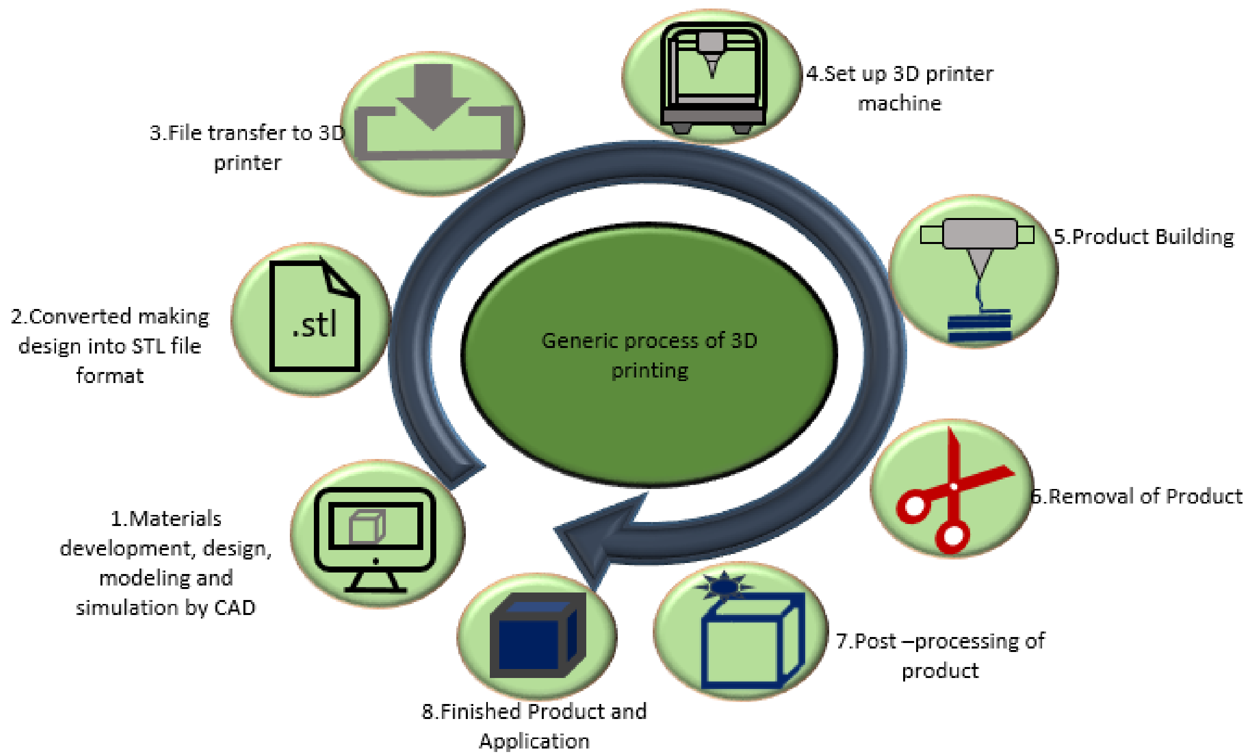


Figure 9. *Eight stages for generic 3DP process of CAD to Product, based on* [69, 76]

For advancing the 3DP technology, a notable number of research works are being conducted worldwide. Howevever, there has been very little research on customers' opinions and perception about this technology [80]. Walker and Corral [81], Spahiu et al. [7] attempted to identify if the customers are willing to buy and use 3D printed cloths. Because of the low manufacturing wastage and personalised garment production [82], the majority of respondents of different studies believe that 3DP will be beneficial for garment production but garments produced through the traditional way cannot be replaced by this new innovative technology just yet [7, 81]. So, 3DP still not in the level where we can use it to manufacture everyday textile clothing [48].

It is apparent that, there are some factors like product features (such as compatibility, aesthetics, usefulness), consumers' confidence (such as self-efficacy) and approach, communal impact (such as the subjective norm) [83], individual principles, and innovativeness [84], stimulate customers' attraction toward 3DP products. A study by Perry [85] showed that acceptance of

3DP product varies from customer to customer based on aesthetics property and performance of 3DP items as well as positive technological views of customers. It has been concluded from a survey conducted by Perry [86] that customers are more interested in 3DP accessories than clothing. The participants of this survey had a positive attitude toward the 3DP system but they expressed their concern about people losing job and abolishing the systems of traditional vending and distribution [86]. The main reason behind the public concern about losing jobs is that 3DP is an extremely automated process and most human workforce is required only during the pre and post-processing systems such as handling and transporting raw materials or finished products [87, 88]. On the other hand, 3DP needs skilled operators for performing manufacturing activities properly, and arranging proper training for the operators becomes quite problematic for under developed and developing countries [69, 88]. On the other hand, because of the development in the field of 3DP technology, it will be possible to create a bespoke product more easily by the customers which will open new possibilities to enhance the understanding of non-technology compliant consumers and bring the manufacturing process closer to them [89]. The advent of 3DP technology seems to enable us all to become designers. Anyone using a 3DP can turn their imaginary design into a real product which will lead to the creation of the next wave of manufacturing entrepreneurs [90]. Moreover, 3DP techniques getting popularity to those who want to produce Do-It-Yourself (DIY) product or making their own clothing at home [86, 89]. So, purchasing personal or consumer 3D printers is achieving popularity day by day because of its easy affordability and ease of use for customers [91, 92]. The **Figure 10** represents the number of 3D printers sold over the range of years from 2007 to 2015. This figure reinforces the statement that, 3DP is gaining popularity at an exponential pace.

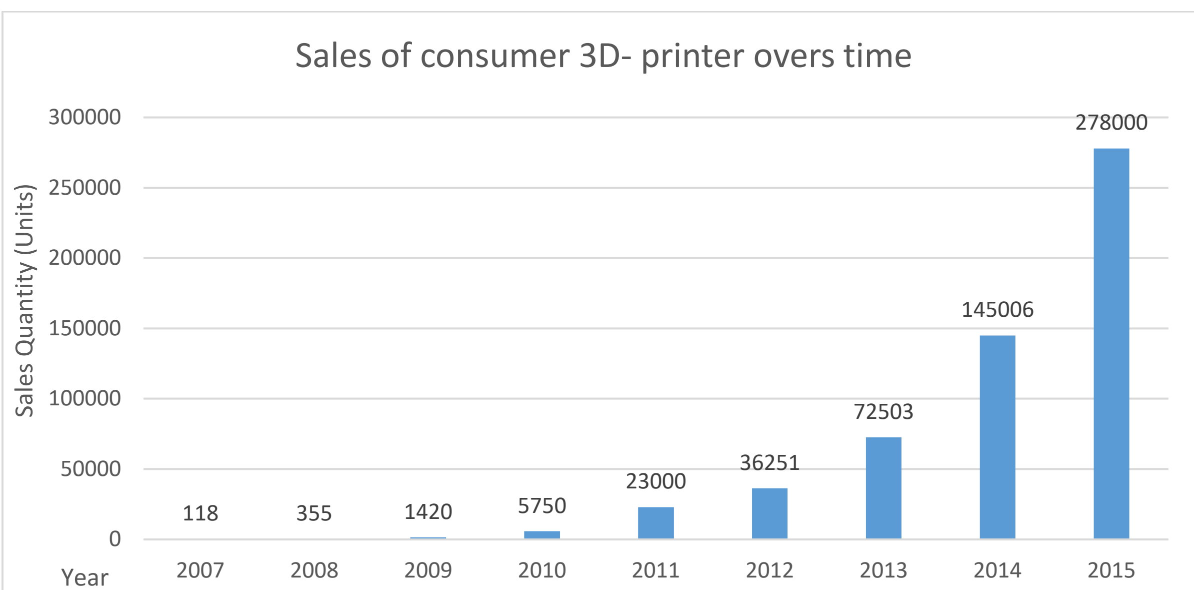


Figure 10. Increasing trend of consumer 3DP sales over time customers [91, 92], Recreated with permission from [92], *Copyright © 2016, Emerald Publishing Limited*

4. Types of 3DP techniques

As presented in the **table 1** and **figure 1**, 3DP technology has gone through a series of development stages in the last four decades. , There are seven principle categories of 3DP techniques according to the ASTM Standard F2792, as shown in the **figure 11**. These are binder jetting, directed energy deposition, material extrusion, material jetting, powder bed fusion, sheet lamination, and vat photo polymerization [93]. Some of their commercially popular derivatives are SLA, SLS, FDM, digital light process (DLP), multijet fusion, polyjet, direct metal laser sintering, electron beam melting, etc. [94]. According to a market analysis done in 2020, 3DP market is worth USD 13.78 billion USD and is expected to expand at a compound annual growth rate (CAGR) of 21% between 2021 and 2028. A large variety of models of both domestic and industrial 3DP machines are available on the market, which are based on any one of these techniques [95, 96].

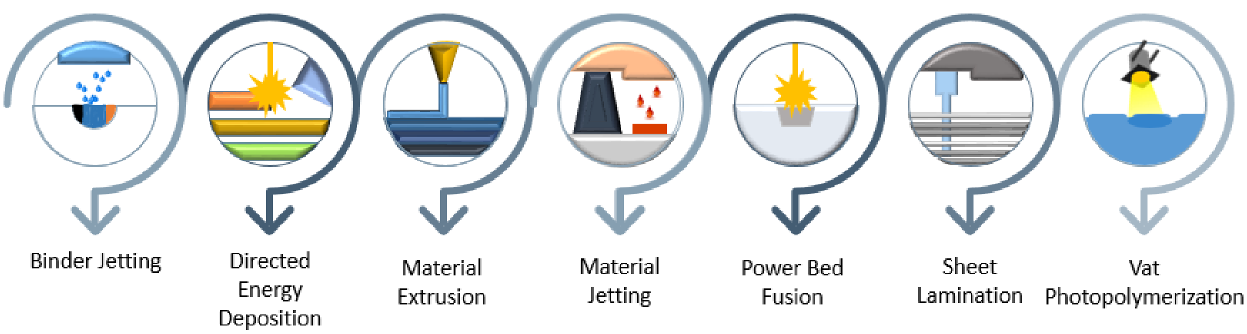


***Figure 11**. Seven principle categories of 3DP techniques according to the ASTM Standard F2792*

4.1 Binder jetting

This method uses any suitable powder-based chemical binding agent, which is sprayed in the form of a jet onto the already scattered powder to form a layer. A 3D structure is then created by making a new layer on top of the previous layer by this process [97]. Sintering is done to consolidate the structure after it is shaped [98]. A broad range of polymer composites, ceramics and metals can be printed by this method. Calcium sulfate hemihydrate, poly-methyl methacrylate (PMM), bronze, Inconel 625, alumina, silica, and titanium dioxide are some of the common elements that can be printed in binder jetting [99]. The advantages of these techniques are the possible widest selection ranges of materials, shaping at room temperature, comparatively faster production than other 3DP processes and the possibility of making slurries with higher solids loadings. On the other hand, multi-step processing, lower relative density, and higher surface roughness are some of the drawbacks of this process [100].

4.2 Direct energy deposition (DED)

In the DED process, a material is melted and deposited on a substrate to create a 3D structure. A specific region is supplied with energy to simultaneously heat the substrate and melt the print material required to be deposited onto the substrate's melt part [99]. This process is preferred for metals and metal-based hybrids, although it can also be done with materials like ceramics in the form of powder or wire. Focused energy sources, such as electron beams, laser beams, and arcs, can be employed for melting purpose [101]. Direct Metal Deposition (DMD) and Wire and Arc Additive Manufacturing (WAAM) are the examples of techniques that fall under this category [102].

4.3 Material extrusion

In this technique, a thermoplastic or composite filament is extruded through printing head nozzles and printed in a layer-by-layer deposition fashion on a surface to create a three-dimensional structure [103]. Its advantages to reduce cost and time and the possibility of creating complex structures have made it widely used in diversified application areas like aerospace, architecture, automobiles, and medical devices [104]. FDM, robocasting and multijet modelling (MJM) are the example of 3DP methods that work based on this principle. Thermoplastic polymers, composites, highly filled polymers with ceramic or metal, and highly filled inks with metal or ceramic powder can be printed in this process [93].

4.4 Material jetting

It is a 3DP category in which structures are made by depositing liquid droplets of photopolymers through printing heads and subsequently curing the deposited photopolymers with various energy sources, such as ultraviolet lamps [105]. The photopolymers can be deposited on the surface following three distinguished techniques - continuous inkjet, drop-on-demand (DOD) inkjet, and polyjet 3D printing [106]. Different photocurable polymer substrates and composites can be printed in this type of 3DP technique [25].

4.5 Powder bed fusion

In this technique, the application of either an electron beam or a laser allows the layer of printing material powder to be melt or fused together to shape an object. Then, another powder layer is laid down, and fusing or melting is carried out again. In this way, the layers are developed one upon another to make the ultimate structure of the object [20]. These techniques can be used for polymers, ceramics, and metals. Direct Metal Laser Sintering (DMLS), Selective Laser Sintering or melting (SLS or SLM), Electron beam melting (EBM) are the techniques included in this category [107].

4.6 Sheet lamination

In this type of 3DP, an object is developed by bonding or stacking material sheets together. The feeding of material is done as a continuous sheet carried by a package. Typically, the material is wound around a spool. The sheet is taken over the building platform and is attached to the previous sheet. A laser cutter or a knife is then applied to cut the contour line of the shape cross-section [108]. LOM and ultrasound additive manufacturing (UAM) are two of the common techniques in this category of 3DP [109]. Polymers, ceramics, metals, glass fibres, composites, etc., are substrates that are suitable for this technique [110].

4.7 Vat photo polymerisation

This is a 3DP process where a liquid photo-reactive polymer (known as photopolymer) is placed in a vat and cured using laser, light or ultraviolet (UV) rays as per the required shape. Photopolymers and ceramics can be used to make objects in this process. The ceramic is used in powder form mixed with photopolymeric resin [97]. The examples of vat photopolymerisation are SLA and digital light processing (DLP) 3DP technique [99].

The Table 2 shows different 3DP techniques in a categorised format with compatible input materials

Table 2: 3DP techniques and materials

ASTM category	Example of technologies	Input Materials	Reference
Binder Jetting	3D inkjet technology	Polymers, Composites, Metals, Ceramics.	[99]
Direct Energy Deposition	Laser Engineered Net Shaping (LENS), Laser Deposition (LD), Plasma Arc Melting (PAM), Electron Beam (EB)	Ceramics, Polymers, Hybrids.	[101, 102]
Material Extrusion	Fused Deposition Modelling (FDM), Fused Layer Modelling (FLM), Fused Filament Fabrication (FFF).	Thermoplastic polymers, Metals, Composites.	[93, 111]
Material Jetting	Continuous Inkjet, Drop-on-Demand (DOD) Inkjet, PolyJet 3DP	Polymers, Ceramics, Composites, Hybrid.	[25, 106]
Powder Bed Fusion	Electron beam melting (EBM), Selective Laser Sintering or Melting (SLS or SLM), Direct Metal Laser Sintering (DMLS)	Polymers, Ceramics, Metals, Composites.	[107]
Sheet Lamination	Ultrasound Additive Manufacturing (UAM), Laminated Object Manufacturing (LOM)	Polymers, Metals, Ceramics, Composites.	[109, 110]
Vat Photo polymerization	Digital Light Processing (DLP), Stereolithography (SLA), Continuous Liquid Interface Production (CLIP).	Photopolymers, Ceramics	[97, 112]

4.8 3DP technologies utilised in textiles and fashion industries

The working principle of some common 3DP technologies like FDM, SLA, SLS, LOM, DLP, and CIJ that are commonly being used in the fashion and textile industry [48] are briefly described below sections..

4.8.1 Fused deposition modelling (FDM)

The FDM process (as shown in the **figure 12**) horizontally deposits a molten printing material, usually thermoplastic in nature (such as ABS, PLA, etc.), extruded through a device called nozzle head to fabricate 3D parts in a layer-by-layer basis upon a base material or platform [113]. The printing element (usually in the form of a filament) is melted inside a liquefying chamber by raising its temperature over the material's melting point and subsequently extruded through the nozzle to create a stream of the molten filament. Then, the extruded polymer is laid down on a supporting structure to create an object by building the layer above the layer. Following slices from the CAD file, each layer begins with the object's contour following by the filling mechanism. The controlling parameters of FDM are the filament feeding rate, extrusion width, linear plotting speed and layer thickness, etc. [114, 115]. Makerbot's replicator desktop 3D printers are being used for fashion industry [116–118]. The "Verlan" and "Bristle" dresses were developed back in 2013 with these FDM printers using PLA and some other flexible filaments [117, 119]. A recent study conducted by Ishack and Lipner [120] reports the development of customised face mask seal for N95 face mask using the FDM 3DP. Normal mesh fabric printed with flexible materials on it by FDM 3D printer is being used to manufacture bags and shoes for its enhanced rigidity and style [121]. Nike's Flyprint is one of the first FDM 3D-printed textiles. It is being used in footwear industry for its superior performance [122]. More FDM based 3DP garments have been reported in section 8.3 of this paper.

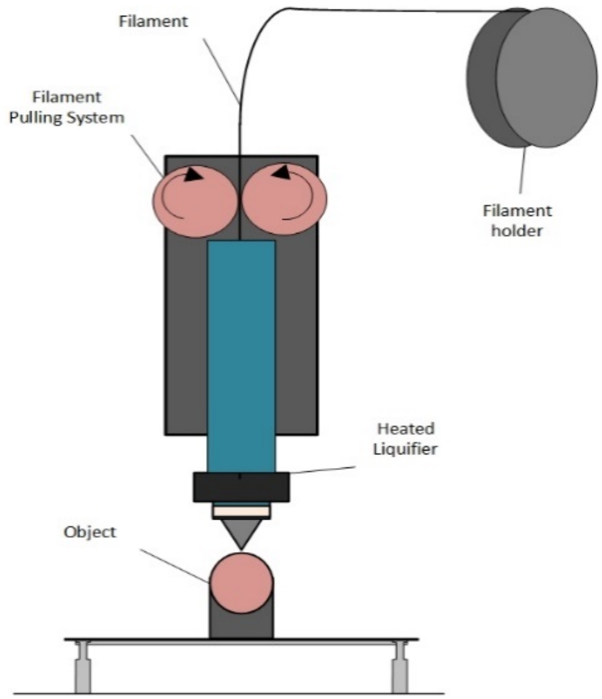


Figure 12. *Schematics of FDM 3DP method, Recreated with permission from* [115]*, Copyright © 2015 Elsevier Ltd.*

4.8.2 Stereolithography (SLA)

Stereolithography (SLA) 3DP, (as shown in the **figure 13**) is a popular additive manufacturing technique that incorporates a UV light source to instigate rapid polymerisation and crosslink of photoreactive polymers, such as acrylates, epoxy, polyesters resins to design and build 3D shape in a layer-by-layer fashion [123]. The company 3D Systems Inc. introduced the first commercialised SLA apparatus in the market. In this process, a high-resolution laser beam is placed above a vat of photopolymer resin. The resin is subjected to hardening according to a predetermined depth and one layer of the slice at a time. The elevator platform moves down at a prescribed length after each layer is completed is polymerized. Finally, all the layers are polymerised to build the ultimate object held by the elevator [124]. Curing time, UV light intensity, polymer concentration, post rinsing time and temperature, and movement of laser and elevator are the controlling parameters of SLA [125]. Dutch designer Van Herpen, Austrian architect Koerner and a Belgian company “Materialise” collaborated in developing a semi-transparent dress using the Stereolithography 3DP [126]. Further, Materialise has a mammoth SLA printer used for printing 3DP dresses [127]. More SLA based 3DP garments have been reported in section 8.3 of this paper.

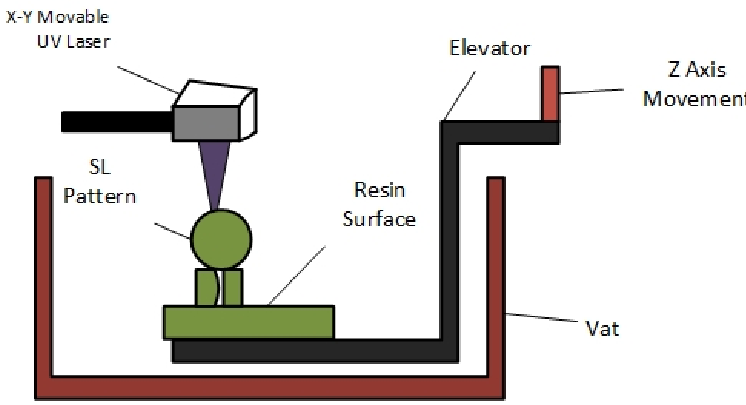


Figure 13. *Schematics of SLA 3DP method, Recreated with permission from* [124]*, Copyright © 2002 Wiley Periodicals, Inc.*

4.8.3 Selective Laser Sintering (SLS)

This technique makes use of computer-controlled laser technology to make objects layer by layer with slicer software. Then the object is developed by selectively fusing powders of the chosen material deposited sequentially in layers with a scanning laser beam. Each scanned layer represents a solidified cross-section of the object's sliced CAD model [128]. Solid-state sintering, chemically induced binding, liquid phase sintering – partial melting, and full melting are the binding mechanisms of SLS [129]. In this process, a powder deposition method successively deposits thin layers of powders (typically 0.1 - 0.3 mm thickness) on a container for sintering [130]. Various polymers, metals, ceramics can be used in SLS. Powder type, laser type, and manufacturing strategy control this 3D printing method [131]. The schematics of SLS has been depicted in the **figure 14.** SLS 3DP has been used to make strong textiles for opera costumes [132]. Some flexible fabrics made of Nylon has also been developed by DIGITS 2 WIDGETS recently [133]. San-francisco's "Continuum" in collaboration with "Shapeways" made a SLS printed bathing suit using Nylon 12 from the measurement provided by their customers through their website. The product has fabric like feel with waterproof properties [134–136]. Moreover, Nike already used this technique to fabricate lightweight plates attachable to their products Vapor Laser Talon and

Vapor High Agility cleats [137, 138]. More SLA based 3DP garments have been reported in section 8.3 of this paper.

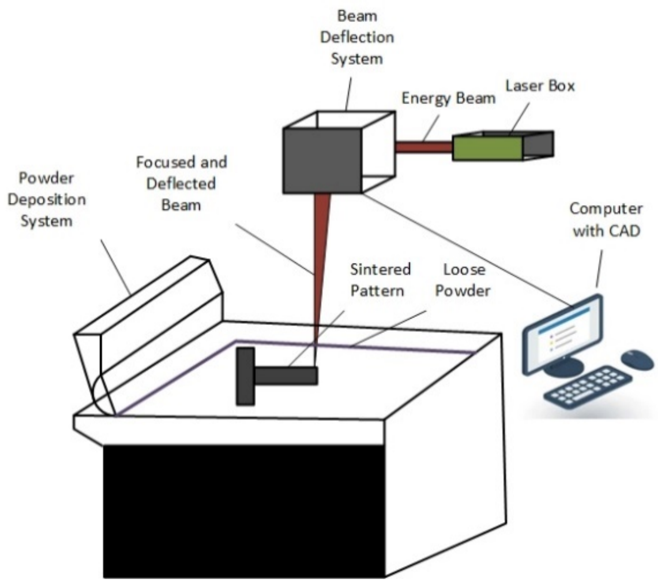


Figure 14. *Schematics of SLS 3DP method, Recreated with permission from* [130] *Copyright @ 2003, Emerald Publishing Limited.*

4.8.4 Laminated Object Manufacturing (LOM)

In the LOM technique, 3D parts are built in a sequential sheet of layers from a roll of material (as shown in the **figure 15**). The lower parts of sheets are coated with thermally activated adhesive. They are laminated by a heated, stainless steel roller that applies the required pressure to put the new layer in contact with the old layers that were previously bonded together. Heat is applied to form the new bonding. Then the layers are cut using a laser beam to a cross-section predesigned by the computer-aided design (CAD) file to make the desired 3D object. Materials which are redundant are cut off in a cross-hatch manner. And LOM 1015, LOM 2030, LOM 2030 E are presently the three types of LOM [139]. This method was first commercialized by Helisys, Inc. (Torrance) in 1991 [140]. Various polymers, ceramics, metals and composites can be used in LOM in sheet form [141]. Roll temperature, lamination speed, laser speed, laser intensity, layer dimension and angle of orientation are the main control parameters of this 3D printing method [115, 142]. However, LOM's production capabilities are limited by the facts that it is not much efficient in creating complex shaped or hollow products when compared to other available techniques [3].

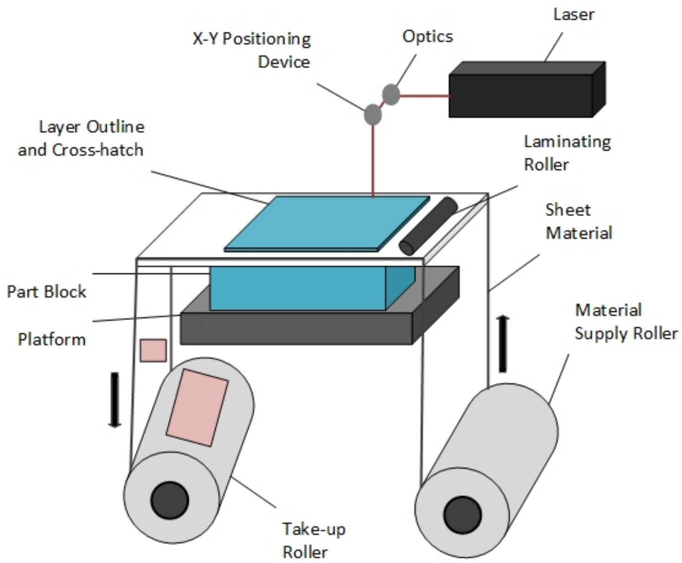


Figure 15. *Schematics of LOM 3DP method, Recreated with permission from* [139] *Copyright © 2000, Emerald Publishing Limited*

4.8.5 Digital Light Processing (DLP)

DLP technique uses a spatially-controlled solidification of photo curable resins through a digital light projector system, including a light projector and a digital micro device (DMD) to produce 3D objects, as seen in Figure 16 [143]. The main components of a DLP system are a light source, DLP module, optic lenses, and printing platform. When the system is in operation, the micro-mirrors on the DMD chip are independently moved to two different directions, according to the corresponding white or black pixels in the mask pre-loaded in the DLP module. Thus, the incident light is selectively reflected according to the design of the object. Next, the printing platform is illuminated by a projection of reflected light through optic lenses, which reserves the photosensitive material. And finally, the material is photo cured and form the solidified 3D object [144]. Various materials like plastic, ceramic, metal, nano-composite can be printed using this technology with the combination of photopolymers [145]. Light intensity, light exposer time, photopolymer absorption properties are the control parameters of DLP 3D printing [146]. The schematics has been shown in **figure 16**. A fabric has been developed by DLP 3D printing using the polyurethane acrylate photopolymer as printing material [147].

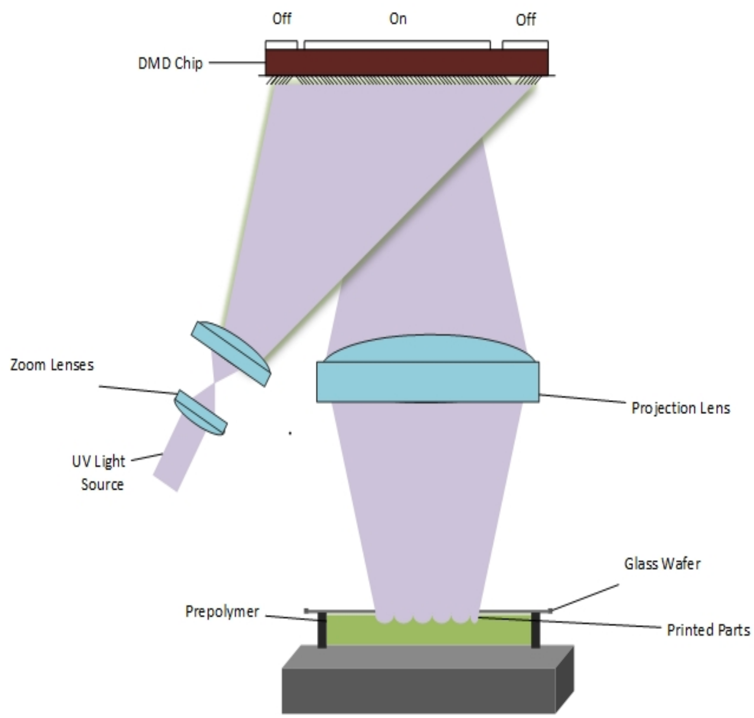


Figure 16. *Schematics of DLP 3DP method, Recreated with permission from* [144]*, Copyright © 2019, Elsevier Ltd.*

4.8.6 Continuous Inkjet (CIJ)

In this 3DP system, a pressurised liquid stream of the printing material is produced through a nozzle head that is segregated into droplets with a piezoelectric element. Continuous and consistent droplets of uniform shape, size and spacing are created with a capillary wave in the fluid stream by simulating the piezoelectric element at a high frequency (generally in the range of 20 to 80 kHz [148]. Selectively charged droplets in the CIJ printing head are deflected by high voltage deflector plates to create the substrate model according to the design. It happens while the droplets are passing through an electrode channel. A gutter captures the uncharged droplets, and then droplets are recirculated for reuse [149]. The adjacent drops coalesce with each other on the surface as per the pattern and transformed into a solid-state to create the designed object. The solidification is done by various processes, such as gelation induced by loss of solvent, cooling down to the solidification temperature, or polymerization by an external agent such as temperature or radiation, etc. [148]. The first commercial device for CIJ was introduced in 1951 by Siemens [150]. Materials like metals, ceramics, biopolymers, thermoplastic polymers, graphene etc., can be printed by the Continuous inkjet (CIJ) 3DP system [151]. The CIJ technique has been shown in **figure 17**. Stratasys developed a PolyJet Technology to directly 3D print on fabric which is used to make dresses with fashion designer Julia Koerner and Ganit Goldstein for the New York Fashion Week [152].

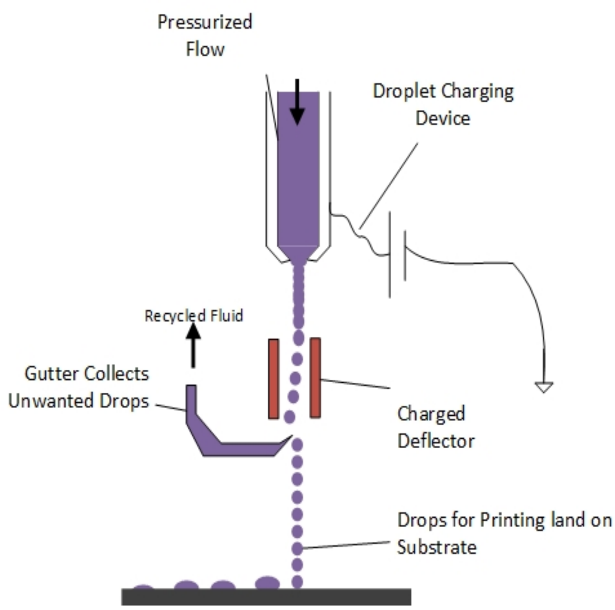


Figure 17. *Schematics of CIJ 3DP method, Recreated under a creative commons [license](https://creativecommons.org/licenses/by/4.0/) (https://creativecommons.org/licenses/by/4.0/).* [149], *Copyright © 2015, Elsevier LTD*

5. Software used for 3DP

3DP is a computer-aided process [8] where virtual design and slicer are used to create printed parts layer by layer, as shown in the **figure 18** [153]. According to Gershenfeld [154], 3DP is a sort of social transition that turns data into things and things into data. Thus, a knowledge based economy can be envisioned from it. 3DP from textile and fashion's context can start with a 3D graphic tool for rendering, modelling and animating the product virtually [155]. Virtual modelling is typically a product of acquired image or scanned structure data of the particular object to be printed [9]. Park and Lee [4] explored the importance of 3D scan data to achieve maximum shape compatibility. Additionally, The requirement of virtual modelling is justified from the fact that, traditional 2D based pattern design accounts for 4-6% of the total garment cost [156]. With virtual modelling, this cost can easily be saved. The CLO 3D [157], Lectra Modaris [158], Optitex [159] are some of the popular software used for virtual modelling, rendering or animating of fashion products. Commonly every 3DP process initiates with generating a model of the intended product using a modeling software [160]. Geometric modelling technique is applied at the preparation stage via a computer-aided design (CAD) software. Software like Rhinoceros [161], 3D Studio Max [8], etc., can create virtual prototypes from real-world measurements and references. Several 3D modeling and visualising software are being used by variety of 3DP techniques for customization and validation of the printed part before proceeding to the next stage. Autodesk 3DS max [155], Fusion 360 [162], Maya [163], Blender [164], Solid work [165], etc. are some of the popular ones in this area. Additional supporting software like ANSYS allows the user to analyse models retrieved by simulator programs [161]. Such 3D design is then moved to a slicer software in the surface tessellation language (.stl) format. Apart from STL, there are some other popular formats are object (.obj), filmbox (.fbx), standard for the exchange of product data (.step), drawing (.dwg), etc. [166]. The purpose of the slicer software is to partition the printing part into several 2D layers to be fed to the actual 3D printer [9, 167] to print the structure at a defined orientation layer by layer [168]. The Ultimaker Cura [169], Simplify 3D [170], Slic3r [171], etc. are some of the popular slicer software. A numerically controlled programming language is produced by an automatically rendered G-Code [172], which deciphers coordinate to 3DP machine and provides movement command [29, 173]. **Table 3** accumulates some of the most used software for 3DP along with their functions.

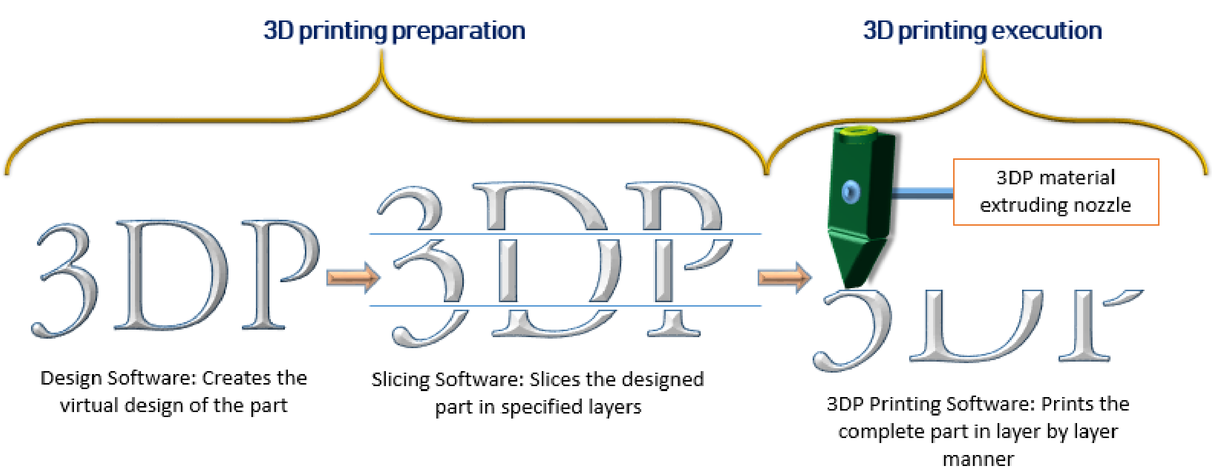


Figure 18. *Steps involved in digital image processing in 3DP software systems*

Table 3: List of some software compatible with 3DP technology

3DP stage	Function description	Example of software	Associated 3DP technique	Reference

Pattern making and visualization	To design and simulate 3D fashion products specially garment and provide a virtual yet true to life visualization	**CLO 3D**	N/A	[157]
	To make virtual patterns and prototypes with high efficiency	**Lectra Modaris**	N/A	[156, 158]
	To cover different parts of fashion design including 2D/3D pattern making 3D prototyping for fashion and apparels	**Optitex**	N/A	[159]
3D simulation	To record customized body data recorded by scanner	**Artec Studio 14**	FDM	[174]
	To print final product of customized clothing	**Franklin Software**	FDM	[175]
	To print final product of customized clothing	**CLO Virtual Fashion LLC**	FDM	[174]
	To create virtual product prototype using real world measurement and reference, it can also be used as a 3D modelling tool	**Rhinoceros**	DDP, FDM, DLP, SLA	[8, 30, 147, 161, 166]
3D design and modelling software	To generate 3D CAD data	**Autodesk Fusion 360**	FDM, SLA	[162, 172, 174]
	To generate virtual 3D modelling, animation and visual effects of the design	**Autodesk 3DS Max**	FDM, SLA	[155]
	3D modelling, animation, rendering software. User is capable of shaping 3D objects with intuitive modeling tools	**Autodesk Maya**	FDM, SLA	[163]
	To design auxetic shapes used for printing	**Autocad Inventor®**	FDM, SLA	[27]
	Model different textile and textile-based structures	**Blender™**	FDM, SLS	[164, 167]
	To design the model for 3DP	**Solid Works**	FDM	[165, 175, 176]
	To create virtual design by code based assembly of the parts and design part with different geometries	**Autodesk Tinkercad**	FDM, SLA	[7, 177, 178]
	To process customized body data recorded by scanner	**Geomatic Freefrom Plus**	FDM	[174]
	To model the specimen	**Geomagic Design X**	FDM	[2]
	To design 3D auxetic sinusoidal pattern	**Autodesk 123D**	FDM, SLA	[179]
	To generate 3D model from 3D scanner (zSnapper)	**ViALUX**	FDM	[29]
	To clean, smooth and revise scanned data and provide accurate 3D surface model	**Geomagic Studio 12**	FDM	[29]
Other helper software	To control the ink loaded robot arm and deposit the inks on a mobile platform	**CRTR Robot Editor**	DW	[180]
	To perform the structural analysis of the 3D model	**SolidWorks 2016**	-	[2]

Slicing software	Their main function is to slice the 3D CAD models in to layers and generate data for machine. They transform 3D designs into instruction that 3D printers understand. They convert 3D CAD information in to 2D layer format.	**Ultimaker Cura**	Almost any 3D printing	[1, 169, 175, 176, 181]
		Simplify 3D	FDM	[30, 170, 174]
		Slic3r	FDM, FFF, SLA, DLP	[29, 171]
		Repetier	FDM	[182]
		OctoPrint	FDM	[183]
		KISSlicer	FDM	[184]
		EOS RP tools	SLS	[185]
G-code generator	To create G-Code for printing	**Chitubox**	FDM, SLA	[172]
	To convert 3D pattern into printable G-code file	**Cubicreator**	FDM	[2, 4, 179]

DDM = Direct Digital Manufacturing, DW = Direct Write

To 3D print any object, selecting the right software to design the 3DP product is crucial [3, 186]. However, nowadays, different 3D software and printers available on the market have a limited build capacity to design and print whole a clothing item in a sole operation [118, 186].

6. Ingredients (inks) and reinforcements used in 3DP techniques

The ingredients or materials of the 3DP inks come from different polymeric origins. According to their origin, polymers are divided into two groups: synthetic and natural [187]. On the contrary, combining various materials of different forms can display the unique characteristics of each constituent member apart from providing any special features that are impossible to achieve by a single element of the composites prepared. A composite may be a homogeneous mixture of its elements. Nevertheless, the individual member parts can remain unchanged and confer their unique characteristics on each other without losing their distinct identity or feature [188]. The materials used for 3DP often comes in different forms, i.e. solid filament [35], powder [189], liquid. Here these three types of materials - natural, synthetic and composites used in 3DP and their forms, will be discussed.

6.1 Natural materials

Natural printing polymers, also known as biopolymers are derived from organic elements, either extracted from any plants or generated by any living organisms [187]. The filaments used for 3DP rarely comes from natural sources as natural filaments cannot be used directly on FDM [9]. [190]

prepared hydrogel ink using cellulose and water to apply in a manner called controlled collapse, which increased the print resolution after drying. Nonetheless, their work suggested the possibility of the use of cellulose nanofibrils (CNF) in 3DP, providing a new dimension towards a more sustainable and biodegradable 3DP technique. When a natural filament is to be used, it needs proper modification. However, it is not rare to use virgin natural polymers as filaments. There are cases where the filaments were found to be very efficient to apply. Rigid cellulose acetate and derivatives were also used for functionalizing textiles, and prototypes were also studied for a design-driven approach [28]. The induced internal affinity of the cellulosic material also enhances the chance of using it as a print paste. It does not require glue or other additives, an all-cellulose approach allowing more sustainable textiles [191]. Cellulose derivative-based composites improve properties make them popular for different fields, including smart textiles [192]. Cellulose nanocrystal provides a necessary toughness, improves mechanical and surface properties for 3D printable bio-polymer [193]. 3DP that applies cellulosic materials for surface tailoring of cellulosic textiles eliminates labour-intensive processing, improves mechanical durability and attach functionalities like refractive and thermos responsive elements on textiles and paves the way for new process with minimal material usage [28]. Also, bamboo fibre-reinforced composites are significant to be used in 3DP [194]. Moreover, 3DP of wood fibre biocomposites has to lead to sustainable production [195]. Despite having some difficulties, the additional manufacturing facilities are looking forward to advancing and progress this kind of natural material. TamiCare's Cosyflex™ 3DP technology can print fabric structure directly from short natural fibres like cotton and rayon mixed with polymer solution [186, 196].

6.2 Synthetic materials

Before the introduction of composite filament, synthetic filaments were very common and popular for use in 3DP. The requirements for successful 3DP and apply them industrially involves some properties such as tensile strength, melt flow rate, breaking load, breaking strength [179, 197]. Different types of filaments were researched to enhance these properties and successfully produce a better synthetic polymer for producing filament. The scope and potential of synthetic polymers are promising, especially PLA [45, 167, 198]. In FDM, materials such as PLA, ABS, and Nylon 6,6 have been highlighted because they were represented in some recent 3DP approaches, whereas more exotic components are seldom used [45, 68, 199].

The PLA and Nylon also used for printing garment clothing [7, 45, 167]. In 3DP, FDM is used to print the molten polymer filament; it is also used for metal oxide semiconductors. Electro conductive material tested by laser-assisted writing and metallic inks; in this case the tensile strength increases and same as elongation at break. PLA has found its usage in medical application, PLA has the best degradation property, and adhesion force is good. It is self-repairing and self-implant. In case of bronzofill filament shows low elongation at breaks. PLA is higher elongated and has higher tensile strength. Recently, researchers have discovered that 3DP techniques are able to print lightweight, lace-like, bright and shiny textures through soft PLA [3, 167]

The mechanical behaviour of virgin ABS polymer was inspected by comparing FDM against the injection moulding. The mechanical behaviour of injection moulded ABS showed superior characteristics in all the tests. Adding to that, being both flexible and strong, ABS offers additional movement, rendering them perfect for joint creation [3]. However, the matured ABS is found to be often too brittle for the desired fine structures. Hard PLA and nylon used in SLS printing can also be very hard for typical textile applications such as garments. Nevertheless, soft PLA, combined with less flexible materials such as BendLay can reproduce textile-based structures [167]. Another report highlights, Belgian company Materialise introduced a lightweight material TPU-92A-1 that showed softer hand feel as well as great elastic nature intended to be used for printing textile products [135]. TamiCare's Cosyflex™ 3DP technology can form fabric directly from liquid polymers like latex, polyamide, silicone, Teflon, polyurethane, etc. [186, 196]

Recycled polyester yarn by using 3DP technology is such a kind example of sustainable production. But 3DP fashion to make sustainable polyester or recycled polyester yarn is still in the theoretical stage [200].

However, another study showed that the choice of adequate parameters in the case of FDM 3DP results in parts of satisfactory properties [201]. So to say, synthetic filaments require a lot more works to increase the probability of applying them on a broader scale.

The Table 4 below accumulate different states at which different 3DP inks are being used in different research works worldwide.

Table 4: Different forms of ingredient inks used in 3D printing

State of the ingredients	Typical Polymer material	3DP technique used	References

Powder	ABS	FDM	[189]
Solid filament	PLA	Extruder-heating system	[35][35]
Solid Filament	PLA	FDM	[167]
Solid Filament	ABS	FDM	[202]
Powder	Styrene ethylene butadiene styrene (SEBS)	Material Extrusion	[203]
Solid Filament	ABS	Melt Extruder	[204]
Solid Pellet	HDPE, ABS	Single screw extruder	[205]
Liquid	CNFs	3D Bio-printing	[190]
Powder	Boron nitride powder	3D inkjet printing	[206]

6.3 Composite materials

The most widely used filaments for 3DPs are composites of natural, metal and synthetic polymers, where synthetic polymers are mostly used as matrix and others as reinforcement. But usually, they are not used in items where they may have to be subjected to mechanical stress as some of the properties of the composites might get weaker than the pure polymeric filament [207]. However, using composites as 3DP inks have their own benefits.

Recent research on synthetic filaments, specifically Nylon 6 [45] white plastic filament and nylon sized fibreglass, showed that the infill structures are responsible for the mechanical behaviour of the composite. The stiffness difference between the fibre and the polymer increased fibre-reinforced composites endurance considerably. However, it should be noted that between interfaces, the fibre-plastic interface was very weak [153].

Polymer-based composites have their unique benefits. These composites containing filler as metal particles such as copper, iron, etc. and ABS as the matrix material shows improved thermal conductivity. Therefore, it is advantageous as FDM machines can fabricate more thermally well-conditioned prototypes that will be more dimensionally appropriate and cause considerable reduction in cycle time for cooling while applied as an injection moulding device component. This type of composites shows a perceptible increment in storage modulus for the greater filler volume. Data reveals, although reinforcing Fe/Cu obviously increases brittleness and lessens the elongation, the break at elongation improves significantly. However, tensile strength drops to add more filler contents as the new material becomes free from additives that ensure better bonding between polymer matrix and iron particles [189].

Cellulose derivative-based composites have shown potential for improving properties, making them popular for different fields, including smart textiles [192]. Cellulose nano crystal provides a necessary toughness, improves mechanical and surface properties for 3DP bio-polymer [193]. In the case of cellulosic textiles, some factors like improvement of mechanical characteristics, reduction in labour-intensive processing, novel functionalities can be achieved by using cellulosic elements for surface modification. It also paves the way for new process with minimal material usage [28]. Also, bamboo fibre reinforced composites show significant characteristics to be used in 3DP [194]. Research shows that combining cellulose nano fibrils (CNFs) with PLA as a matrix with melt extrusion process also provides bio-composites that improves both tensile strength and elongation at break printed with currently available FDM printer [1]. Adding to that, further investigation on PLA based composites confirms that the melt flow rate (MFR) increased for introducing Fe_3O_4 & polyvinyl chloride (PVC) as reinforcement while shows a negative trend for wood powder. At the same time, the process was done with a twin-screw extrusion mechanism [197]. Le Duigou et al. [195] further investigated bio composites, a blend of polyhydroxyalkanoate and PLA reinforced with recycled wood fibres used on an FDM printer. From the experiment, they concluded that mono-material could be used to enhance the recyclability and curtail the delamination between bi-layers during the printing of bio composites.

In the recent years, research works have been conducted with the non-conventional polymer nanocomposites (CNT) and graphene (G) based conductive nanocomposite polymers for functional 3D modeled composition. In such experimental work, polybutylene terephthalate (PBT) acting as matrix polymer yielded high functionality. The structure was also fairly mechanically sturdy and robust. The properties like conductivity, printability, morphology, crystallinity and viscoelastic behaviour of the 3DP construction were assessed. The analogy found that functional characteristics of PBT/CNT 3DP structures showed better aesthetics as well as functional properties, i.e. elastic behaviour and conductive properties compared to PBT/G 3DP structures. For PBT/CNT and PBT/G composites, the optimum parameters and conditions remain more or less unchanged. This is because their share of dispersion in the PBT matrix is a very low volume fraction [208]. Thermal conductivity is one of the vital properties of a metal-polymer composite [189].

Grid like structure slows the RRC (relative resistance change) rate. The lower the IFS (inter filament spacing), the higher the compactness, resulting in inaccessible surface area. On the other hand, a higher degree of IFS makes the scaffolds less dense and fewer materials are in contacts. As a result, the conductivity is also lower. The RRC rate is higher than the diameter is higher of the filament. Diffusion is higher when fill-up is high, and the sensitivity of the printing is high. The increase in the layer can cause less sensitivity, and pattern variation is also a factor. For the IFS ranging between 0.2 and 0.6 results in the trapping range between 0.2 and 0.4 g. The increase of scaffold thickness increases liquid trapping and the low conductivity and higher the applied voltage, the electrical conductivity and the solvent cast printing [209]. Higher conductivity printed scaffolds generate a low voltage of sensitivity measure. The sensitivity of the liquid sensor can also be reduced by incrementing the number of printed layer and decreasing the IFS. The pressure and the displacement of the nozzle depends not only on the concentration of CNTs (carbon nano tubes) but also on the viscosity of the prepared inks [209].

Nikzad et al. [189] reported, that the ABS (acrylonitrile butadiene styrene) composite is used with copper or iron powder to increase the tensile properties, fluidity, flexibility and lower the stiffness of a material. Embedding copper particles with high concentration and large size on the matrix of ABS can increase the thermal conductivity. Less volume of copper cannot break the thermal resistance of the matrix, and iron particle have lower thermal conductivity.

3D printed polymers have also been combined directly with textile fibres, yarns and fabrics to create composites, and such union can contribute to enhance mechanical properties [27, 210]

The Table 5 encompasses some of the examples of composite polymers being used for different textile-based 3DP applications.

Table 5: Examples of different composite 3DP pastes being used with 3DP techniques

Composite Polymers/ Matrix	Reinforcing Material	Printing Technique	Advantages	Disadvantages	References
Polylactic acid (PLA)	Virgin PLA Polyvinyl Chloride Wood Powder Fe_3O_4 prepared with twin-screw extrusion	FDM	More strength and functional as break elongation improved slightly Reinforcement increases the MFR (melt flow rate) of composite. Thermally stable	Diminution of peak load, break load and strength at break	[197]
Acrylonitrile Butadiene Styrene (ABS)	Fe powder Cu powder Both at varying percentage	FDM	Flexible filaments Applicable in existing FDM300 machine. It withstands more stress than the pure	Greater Fe and Cu powder percentage tends to clog the nozzle of the printer, which needs very expert handling to overcome	[189]

			polymeric materials		
Dimethyl sulphoxide (DMSO)	Raw polyacrylonitrile (PAN) nanofiber	Electrospinning and FDM	Notable improvement of abrasion resistance	The adhesion between the fibre mats and the polymer still needs to be improved without destroying the nano-mat	[211]
Cellulose nanofibrils (CNF)	Carbon nanotubes (CNT)	3D bio printing	Natural composite and mechanical characteristics can be modified across a wide range by choosing a solidification technique	The structure shrinks after drying	[190]
Polylactic acid (PLA)	Cellulose nanofibrils (CNF)	FDM	Natural composites with Increased thermal stability, water absorption and mechanical implementation	Mechanical pretreatment is required for homogenous characteristic	[1]
A blend of polylactic acid (PLA) and polyhydroxy-alkanoate (PHA)	Recycled wood fibres	FDM	Natural composite with the hygro-elastic behaviour of natural fibres	Comparatively weak mechanical features and high hygroscopic sensitivity. As the filament gets thicker, porosity gets increased, but cohesion gets dropped	[195]
Polybutylene Terephthalate (PBT)	Multi-walled carbon nanotubes (CNT)	FDM	Electrically conductive structures and improved thermal stability	High printing temperature also leads to wearing the nozzle at a noticeable rate	[208]
Polylactic acid (PLA)	Boron Nitride powder	3D inkjet printing	Enhanced thermal conductivity and greater alignment of BNNSs by the lengthwise direction of the fibre is achieved after the hot-stretching technique	Boron Nitride Nano-Sheets (BNNSs)	[207]

6.4 Reinforcement materials

Attachment of high-performance multifilament fibres like carbon, glass fibres textile technology greatly impacts certain enriching characteristics of composites. For instance, the interlaminar shear strength, damage tolerance, reducing the cost of manufacturing etc. [212]. The huge application potential of 3DP textile reinforced composites makes them popular for the rapid manufacturing of structures having various potentialities of integrating novel functions and functionalities [213].

One of the most used reinforcing components is glass. Nylon seized glass filament reinforced composites are highly load-enduring and thus are used for prospective and future high-performance applications like building industries, automobile, aircraft etc. [153]. Bilisik et al. [214] highlighted in their study, epoxy glass 3D stitched preform composites possess high mechanical properties and damage tolerance properties. Mechanical performance, flexural and compressive properties are significantly better in case of glass fibre reinforced 3DP honeycomb sandwich composites compared to commercial aluminium and 3DP neat nylon honeycomb structures. Sayilan et al. [215] reported, due to glass fibre reinforcement, a rise in flexural strength by 200 per cent and mechanical responses by up to 5.5 fold in compressive strength is observed. Szykiedans and Credo (2016) [216] further highlighted, 3DP component with polyethylene terephthalate glycol (also known as Z-Glass) or PETG fibreglass reinforcement behaves more like tough materials without yield point.

Another frequently applied component, continuous carbon fibre, plays a promising role as reinforcement material increasing stiffness, strength and design-ability of 3DP polymer parts [217]. Continuous preprocessed carbon fibre reinforced PLA composites have demonstrated higher tensile strength 91Mpa, improved flexural properties (164%), greater storage modulus and better fibre matrix bonding, making them suitable for high-performance usage [218]. Yao et al. [219] demonstrated that Carbon fibre reinforced specimen could be found to provide as much as 70% improvement in tensile strength and 18.7% increment in flexural strength compared with the non-reinforced specimen. Using multiwall carbon nanotube 2% and with high structured carbon 5% to make PLA nanocomposite 3DP filament with conductive properties has been introduced to develop desired functional properties and create efficient production technology [220]. Compared with similar thermoplastic materials without any reinforcement, components' physical and mechanical properties can be improved using reinforced composites. Thickness or weight can also be decreased through short fibre reinforcement [29]. Fracture toughness and fracture energy are found to show improvement in the case of short carbon fibre reinforced PLA composites than neat PLA [219]. The study conducted by Ahrendt et al. [29] established, almost doubled or 30% enhancement in maximum bending stress is achievable by adding 20% short carbon fibre in the

PETG. Therefore, Carbon fibre reinforcement is growing attention in the field of AM by improving mechanical properties of 3DP parts, reducing the time required for producing functional parts and reducing warping [221]. Thermoplastic and thermosetting composites are two of the most utilized elements in 3DP methods. According to Hao et al. [222], the continuous carbon fibre reinforced thermosetting composites shows better mechanical properties than continuous carbon fibre reinforced thermoplastic composites. Experiment conducted by Ming et al. [223] has shown that 3K carbon fibre (3k fibre has 3,000 strands of carbon filaments in each tow) reinforced thermosetting composites shows tensile strength and tensile modulus of 1476 MPa and 100.28 GPa respectively and flexural strength and flexural modulus of 858.05 MPa and 71.95 GPa respectively.

Reinforcement of continuous fibres into the plastic resin of the 3DP model is another promising innovation as it has a significant positive effect on the mechanical characteristics of 3DP composites [224]. Bettini et al. [225] mentioned that incorporating continuous fibres as reinforcement material like carbon, glass, and aramid makes high mechanical performance products that lead them to advanced applications. However, it is also a matter of concern that, evidently, 3DP composites has lack of inter-laminar bonding performance than conventional pre-preg composites (a composite made from pre-impregnated fibres). On the other hand, according to Caminero et al. [226], reinforced composites show a better inter laminar shear strength (ILSS) than the unreinforced ones. Typically carbon fibre reinforced composites show better performance than glass-reinforced composites. Nevertheless, for the versatile application of laminar composites, it is important to improve the interlaminar shear strength [227].

7. 3DP on textile substrates

3DP is applied to the textiles in a different form to make prototype or real-life applications [228, 229]. It can be particularly advantageous in the situations where intricate design and detailing are needed to be combined more precisely than conventional printing method [3]. Researchers are investigating the suitable printing materials appropriate for 3DP on specific textile substrates [230, 231].

Textiles made of natural fibres have unique properties depending on their respective characteristics of origin and has better use for 3D print due to their roughness. It was observed that adhesion successes of printing paste depended on hairiness and roughness and hydrophobicity and wettability of specific samples. Due to the hydrophilic behaviour of natural fibres, print paste penetrates the fabric and thus show good adhesion properties [68]. Wool fabrics show good adhesion property due to its rough surface [232]. Cellulosic fabrics, for example, uncoated and undyed woven cotton, knitted cotton and woven viscose fabrics are used as 3DP substrate where biomaterial like cellulose acetate is used as printing paste as an all-cellulosic approach in 3DP. Most natural substrates show satisfactory print surface ability and good adhesion to the print surface [28]. The **Figure 19** shows floral 3DP pattern on different fabric surface.

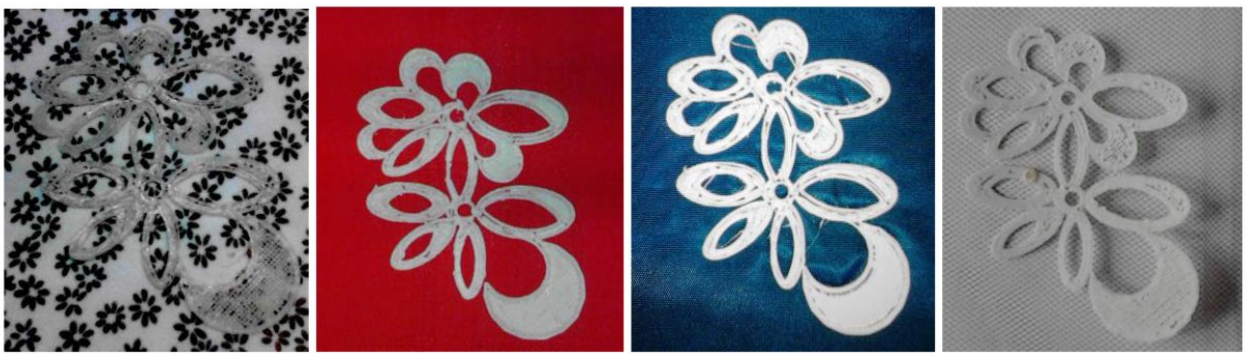


Figure 19. *Floral 3DP pattern on cotton, wool, viscose and polyester net textile substrate (from left to right), Reused under the terms of the Creative Commons Attribution 3.0 licence (https://creativecommons.org/licenses/by/3.0/).* [232]*, Copyright © 2014, IopScience.*

Printability of textiles depends on the topographical property of textile [68]. If a textile susbstrate is too thick and less rough on the surface, it is not easy to print onto it as print paste would not make a sufficient hold onto the surface. Different knit fabric made of synthetic textile fibres such as polypropylene, polyester, polyurethane, polyethylene terephthalate (PET) was used to produce 3D parts that were printed through the SLA process showed good printability [172]. This is because knitted substrates have a more porous surface structure than woven, resulting in form-locking connections with the printed polymer [233].

One of the most common synthetic textile fabrics is made of polyester from PET polymer. Although they are sometimes blended with natural substrates to produce a wrinkle-free, strong, shrink reduced, tear-resistant textile substrate, the popularity of 100% woven or knit structure is also quite high [234]. Research carried out by Graßmann *et al.* ([181] showed that electroluminescent devices can be digitally printed on a textile substrate such as plain woven polyester fabric to create the luminous surface.

Apart from this, functional textiles with improved comfort are being produced by 3DP. For better flexibility, touch, and comfort, protective gearings are mostly printed on the knitted synthetic substrate; a knitted structure made up of loops allows them better stretchability than woven fabric [174, 233]. A good number of protective gears where the material has been 3D printed on a textile substrate can be found [29, 174]. 3DP on the different textile substrate in the protective application has been discussed in chapter 8.4. The **Table 6** shows some examples of 3DP on a different natural and synthetic textile substrate

Table 6: Examples of 3DP on the natural and synthetic textile substrate

<table>
<tr><th>Fibre source</th><th>Fabric composition</th><th>The material used for printing</th><th>Printing method</th><th>Refer ence</th></tr>
<tr><td rowspan="2">Natural</td><td>Woven cotton (plain weave, 100% cotton, 150 g/m$^{2)}$</td><td>Rigid cellulose acetate</td><td rowspan="2">Direct 3D print</td><td rowspan="2">[28]</td></tr>
<tr><td>Knitted cotton (single knit, 100% cotton, 155 g/m^2)

Woven viscose (Bamboo Plain Ivory (BB12), 100% viscose, 140 g/m^2)</td><td>Flexible acetoxypropyl cellulose (APC)</td></tr>
<tr><td>Natural</td><td>Woven, 100% cotton
Woven, 100% linen</td><td rowspan="2">clear 3DP 405 nm UV resin</td><td rowspan="2">SLA</td><td rowspan="2">[172]</td></tr>
<tr><td>Synthetic</td><td>Weft knitted (100% polyester)

Weft knitted/coated (100% polyurethane)

Warp knitted (100% PET)

Weft knitted/coated (100% polyurethane)</td></tr>
<tr><td>Natural</td><td>Woven, 100% cotton</td><td rowspan="2">ABS and Filaflex</td><td rowspan="2">FDM</td><td rowspan="2">[199]</td></tr>
<tr><td>Synthetic</td><td>Woven, 100% PET
Knitted, 100% PET</td></tr>
<tr><td>Synthetic</td><td>Woven polyester fabric</td><td>Doped zinc sulfide pigment as luminous ink, Dielectric ink (a dispersion of titanium dioxide particles), Carbon-containing counter electrode ink</td><td>Direct 3D print</td><td>[181]</td></tr>
</table>

Synthetic	Knitted polyester	Thermoplastic polyurethanes(TPU2-86 85shore hardness)	FDM	[174]
Synthetic	Flat knitted surface (75% Poly-amide 6,6, 18% raw rubber, 7% elastane, 2.7 mm thick, 850 gsm)	Carbonfil 1.75 mm filament Polyethylene Terephthalate	FDM	[29]

Adhesion between printed part and printing surface plays probably the most crucial role in the case of 3DP on the textile surface. The pretreatment of textiles refers to the chemical and physical treatment of fibres or textile surfaces beforehand to improve properties that can promote the functionality and uniformity of surface behaviour. Through pretreatment, impurities, wax, lubricants get removed, which aids in good printability on the textile surface [235]. In case of affiliation with 3DP, scientists all over the world carried out several experiments to see if there is any linkage between pretreatment of textiles and adhesion properties of 3DP material as well as to what extent it has impact over the durability of the printed part over any textile surface.

Korger *et al.* [68] reported that pretratements such as washing and plasma treatment on cotton and polyester fabrics can influecne the adhesion of 3D printed-soft PLA on them. Another study revealed, more hydrophilic fabrics showed better adhesion with 3DP materials through capillary action [174]. The adhesion force of textile cotton and PLA increases with glue stick application before printing. The reason can be elucidating as the glue creates an additional chemical bonding between them while printing. Washing and NaOH also showed a positive result as the pretreatment process [176, 236].

A thin layer of polymer coating on a textile substrate before 3DP could increase the adhesion property. One study showed that coating with poly methyl methacrylate (PMMA) showed strong adhesion for PLA print material, whereas printing with ABS did not appear with a satisfactory result [237]. Additionally, fabric coated with PMMA can be used to increase adhesion for rigid PLA prior to printing; this performs negatively for soft PLA [238].

Besides these physical and chemical treatments, Kozior et al. [211] pointed out another important pretreatment fact for 3DP on nanofibre mat for filtering. They suggested that soaking and drying the electrospun nanofiber mat in pure or soap water before 3DP is advantageous. It supports the relaxation of fabric, and at the same time, the electrostatic charge gets reduced [239].

Sheron *et al.* [240] experimented using the FDM technique on different properties of woven fabric to determine the effect on adhesion strength between woven sample fabrics and PLA. They found that warp density, weft density, and warp linear density affect adhesion but fabric weight and linear weft density did not have any direct effect on adhesion.

Dopke et al. [210] investigated how different parameters affect the adhesion force between a 3DP polymer and various knitted structures made of various materials. They found that the z-distance between the nozzle and the printing bed, in particular, had a major impact on the adhesion forces measured. However, other printing parameters did not have any significant effect.

Grimmelsmann et al. [27] found that there are few relations among textile fabrics, fabric thicknesses and manufacturing technologies. The interactions show that FDM prints on cotton, polyester, wool and viscose can result in great adhesion properties [68, 232]. This result depends on the z-distance between the nozzle and printing bed, which reveals a significant effect on the measured adhesion force [241]. This z-distance is determined by printing one layer simultaneously as the rectangles, later printed on textile fabrics, and using a micrometre calliper to calculate the layer height [210]. With the smaller z-distance, the value of adhesion forces increased remarkably. Just in the scenario of thicker fabrics, the highest noticeable value is almost equal to the thickness of the fabric for the z-distance. Besides, z-distance affects the adhesion forces for using different materials [242].

8. 3DP of textiles

3DP has started to revolutionise the production system in the textile and fashion industry. Traditionally, a garment can be produced from fabric, which is composed of yarns through different machines. In contrast a a complete garment structure can be realised directly through 3DP. . Mainly FDM techniques are used to print on the whole textile fabrics or parts of textile fabrics or garments due to the very low loss of raw materials, greater flexibility, lower expenses and simple handling of appliances and raw materials compared to other techniques [242, 243]. Moreover, the 3DP method has become very popular in technical textile sectors for producing personal protective equipment (PPE) and sensor, electrode, conductor, actuator like electrical equipment through creating textile polymers by various 3DP techniques. Below sections deal with the description of 3DP of textiles based on contemporary works.

8.1 Yarn and similar textile structures

Although 3DP technology has attracted notable attraction from textile or garment sectors, relatively few works have been conducted for producing 3DP yarn structure directly [244]. If we analyse a yarn, we will identify that it is made up of several strands of fibres with various types of cell structure through twisting together. For producing a variation in yarn, different types of texture effects are given. This textured yarn is used where special properties are required. These cell structure and texture effects related to yarn are also possible to be produced by using 3DP technology. Some research activities were performed to discuss yarn type structure like needle felted yarn [245], honeycomb cell-like structure [215], and also a creation of texture [65] through 3DP technology.

By drawing on the concept of 3DP yarn structure, Hudson [245] introduced a prototype 3D printer so that flexible and soft 3D objects can be possible to make by creating needle felted yarn. This printer is called a felting printer that works based on the process of needle felting. For the production of yarn like structure by this type of 3D printer, a barbed needle is continuously passed through a body of fibres so that fibres can be drawn into layers below to create entanglement [245]. Nowadays, 3DP is being used for making woven fabric by creating warp and weft yarn automatically by using a 3D printer based on additive manufacturing technology like FDM. According to this process, for creating a warp and weft yarn, at first, they are designed as separate compounds by using 3D CAD design software and these yarns are grouped together to form one model in *.stl (surface tessellation language) format file. This file is imported into the 3D printer to form plain weave fabrics automatically [204].

Traditionally different types of yarn are prepared from different types of fibre, and we will be able to see various type of cell structures in different types of fibre via microscopic view. To insert traditional textile-like structures into 3D printed textiles, these types of structures are being made using 3DP technology. For instance, the 3DP honeycomb cell was made by using neat nylon and glass fibre reinforcement process [215]. A typical 3DP honeycomb cell structure has been depicted in the **figure 20 (a)**. A complex cellulosic cell structure (as shown in) that allows for the fabrication of foams was printed by using viscous thread instability (VTI) 3DP procedure has been shown in the **figure 20 (b)** [246]. Several layered structures (as shown in the **figure 20 (c)**) were possible to create applying the FDM 3DP technique [167].

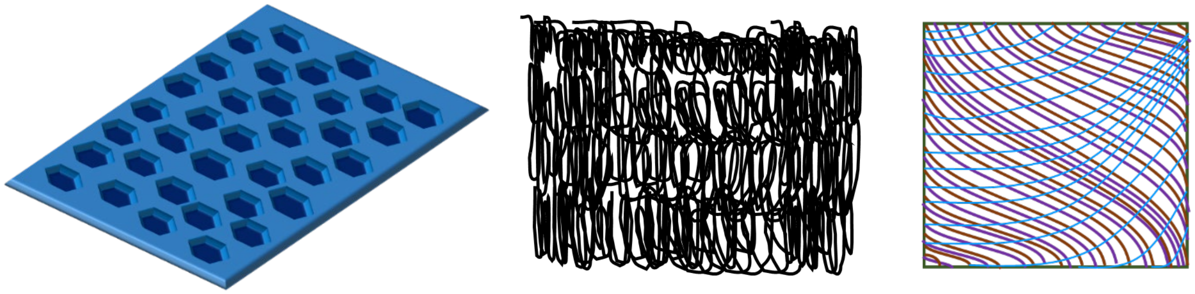


Figure 20. a) *Honeycomb cell structure, Reproduced with permission from* [247], *Copyright © 2018, Elsevier Ltd.* ***b)*** *Alternating loops for making cellulosic cell structure, Recreated under a Creative Commons license (Attribution-Noncommercial) (http://creativecommons.org/licenses/by-nc-nd/4.0/).* [246], *Copyright © 2016, Springer Nature,* ***c)*** *FDM printed 3-layer structure, Reused under the terms of the Creative Commons Attribution 3.0 licence (https://creativecommons.org/licenses/by/3.0/).* [167], *Copyright © 2014, IopScience.*

Yarn surface is not smooth and different textures such as coiling, wrinkling, curling, etc. can exist on yarn surfaces. Different textured synthetic yarn is also created by using various methods such as false twist, edge crimping texturing, etc. method [248]. Because of the improvement of performance in 3DP technology, various texture effects are possible to create, which can considerably promote the development of the apparel industry [249].

A compilation of some recent works where the yarn structures were developed using 3DP technology is presented in the **table 7**.

Table 7: Summarization based on Yarn/Cell/Texture made by 3DP technology:

Machine/3DP Software	Materials	Procedure/Technique/Method	Reference
CubePro Duo Printer from the cubify company	Lightweight, high impact resistant, and high creep resistant polymer: ABS (Acrylonitrile Butadiene Styrene) filament	Warp and weft yarn made from a thermoplastic filament, ABS, through melting for creating flexible textile structures.	[204]
Stratasy-Objet Connex 3D printer	Polyester and cotton	The texture on cloths can be made by combination of 3DP technology and hand-made fabrication. Ink effects and cracked effects can be a way for creating texture.	[250]
FDM principle-based Mark-Forged 3D printer	Nylon filament	Honeycomb designs were developed in SolidWorks® and uploaded as *stl file format to a 3D printer to create honeycomb cell structure.	[215]
Felting Printer works like Fused Deposition Modelling (FDM)printer	Soft fibres (wool and wool blend)	Yarn like shape was produced by needle felting process (by entangling and compressing sheets of fibres using new custom felting print head which can be attached to Fused Deposition Modeling (FDM)printer also.	[245]

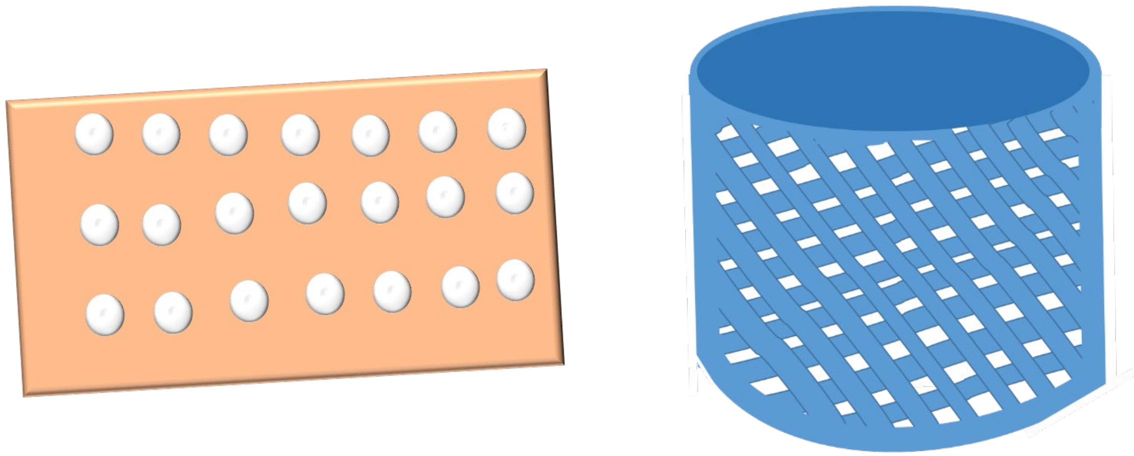
8.2 Fabric structure

Fabric is traditionally made by compiling a large number of yarns. 3DP is being introduced in the fashion industry to print textile fabrics, which are typically bred through a weaving, knitting, and non-woven method as mentioned in the section 2. Traditionally any surface structured made by 3DP technique shows a stiff and solid behaviour, but recent works aimed to create flexible structures that can adapt to the shape and movement of objects [167]. The 3D printed textiles are presented to demonstrate specific parametric relationships between geometry and the behaviour of the overall textile [251]. In order to print a 3D fabric, its structural data must be prepared for the printer in a standardised format [204]. The structural data can be derived either from a 3D scanning procedure if the original object exists or from a design approach using specific CAD programs if the object under consideration is non existing in real [252]. Attempts have been made to produce woven fabrics with sufficient texture and considerable shearing capability [167].

Partsch et al. [204] designed, printed and evaluated three different woven samples having plain weave structure. One of their sample had a classic plain weave pattern with a zig-zag shaped crimp in warp and weft with rounded edges. The dimensions of warp, weft and their distances were in the range of 0.6 to 1.6 mm. The one had a similar structure to the first one like warp and weft with a zig-zag shaped crimp with rounded edges, but the yarn diameters and the distance between the warps had bigger dimensions. The third sample had a round-shaped crimp in the weft but no crimp in the warp yarns. The yarn diameters and the yarns' spaces are in the dimension range of the previous samples [204].

Two approaches are tried to produce inkjet printer 3D textiles. One is to build up a new 3D surface texture on any existing textile. The other is to print 3D textile structures following simulating knit and woven structures as close as possible [253]. In a research work, textile-based structures were 3D printed using SLS and FDM technology [167]. Structures with several typical 3D printing materials and the dependence of adhesive forces on the distance between the textile layer and printing nozzle are tested in [254]. Another study reports the development of a custom textured 3D fabric using primary prototype material such as low-grade polyester and cotton blend [255]. Fabrication of flexible, lace like, glossy fabric from soft PLA with FDM printers have been reported in Melnikova et al.'s [167] work.

Conventionally, the helical interlacement of two sets of yarns in a circular manner occurs to produce tubular braid type textured fabric by running one set of yarns in the clockwise direction and the other in an anticlockwise direction [256]. But using 3DP technology, transversal tubular braid texture (maypole braid) simulating helical yarn configuration has been introduced [161]. For creating texture effect on cloth, a combination of 3DP technology and hand- made fabrication are being tried [250]. Electrospinning, a type of 3DP, can be brought into play to manufacture custom textured 3D fabrics and textiles by varying the mould that is placed inside an electro-loom machine. Still, this electrospinning technique remains in the prototype phase [255]. The **figure 21 (a)** demonstrates a large textured pattern made by 3DP and a tubular braid structure is shown in the **figure 21 (b**)



a b

Figure 21. a) Large texture pattern for a skirt, adapted from [255]*, b) Lattice tubular braid texture. Recreated with permission from* [161]*, Copyright © 2020, © SAGE Publications.*

Lace patterns have been created, inspired by the well-known Plauen lace, containing mostly floral and round elements on a base layer connecting these parts using 3DP. Such a design is depicted in the **figure 22** (left panel). Due to the absence of free-floating areas, printing by the FDM process is unproblematic if all connection lines have large enough diameters (**figure 22**, right panel) [167].

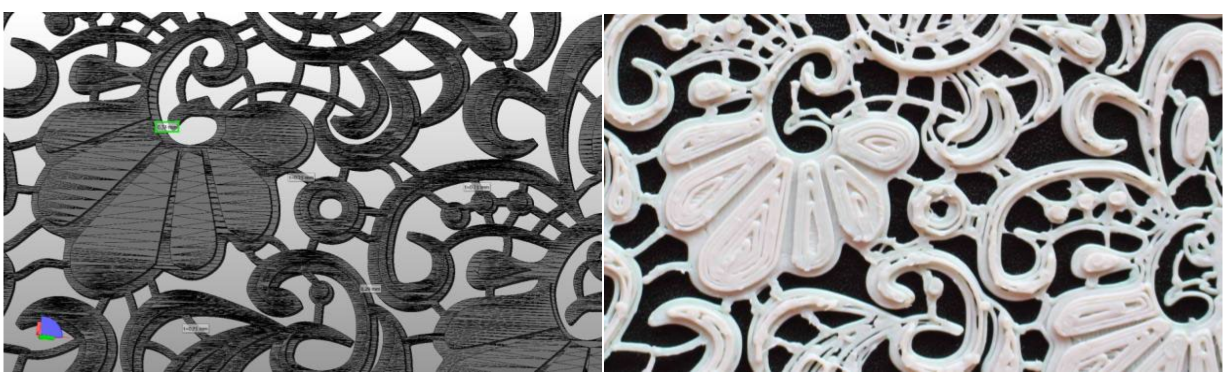


Figure 22. Multi-layer lace pattern, depicted in "netfabb" (left panel), and the resulting 3D print (right panel) - detail dimension ~ 4 cm x 7 cm, Reused under the terms of the Creative Commons Attribution 3.0 licence (https://creativecommons.org/licenses/by/3.0/). [167] Copyright 2014, IopScience.

Traditional knitted structures can be formed by the inter-looping of a continuous thread to create symmetrical loops [185]. In the case of producing knit structure, through the SLS process, the resulting model reproduces the look of a single face weft knitted fabric. However, it should be mentioned that the lack of flexibility of the material itself leads to distinctly different mechanical properties of the model, compared with knitted structures created from traditional textile yarns.

Beecroft [26] printed a single-faced weft knitted structure using a 3D CAD model made in Rhinoceros software system. A single loop unit was initially drawn as curves then piped with thickness. Once created, the cell unit can be repeated to create desired width (courses) and length (wales). The structure has been depicted in the **figure 23**.

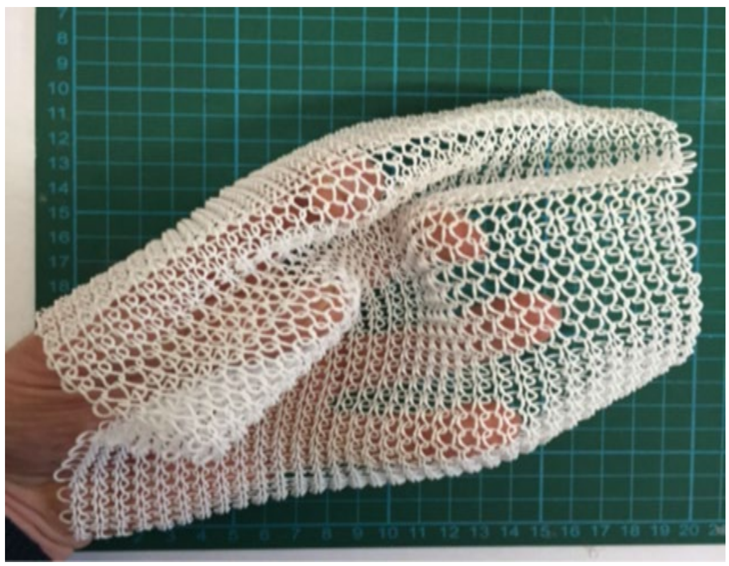


Figure 23. *Flexibility of a 3DP weft-knit structure, Reused under the terms of the [Creative Commons Attribution 3.0 licence](https://creativecommons.org/licenses/by/3.0/) (https://creativecommons.org/licenses/by/3.0/).* [26] *Copyright 2016, IopScience.*

Like the single-faced weft knit structure, the interlock demonstrates great flexibility, bounces back to its original form and stretches across the horizontal courses [26]. To do this, both single-face (plain) and double face (interlock) weft knitted structures were tested to record their compression, extension, stretch and flexibility [185]. Further research into different types of powdered materials, i.e. thermoplastic polyurethane (TPU) may produce softer fabrics, which may be more suitable for a fashion application [26].

Very recently scientists from MIT have developed a mechanically superior fabric that is "soft as skin". The structure is inspired by intertwined pattern of collagen and traditional TPU was found to render the best result as printing material [257, 258]. Further, Jack Forman of the MIT Media Lab has recently introduced a technique to turn the under extrusion defect of the 3D printers into a flexible thin fabric substrate. The product has been named ‘DefexTiles’ which is a woven-like structure of ‘glob-stretch’ pattern [259]. Researchers from the University of Maryland have developed a special kind of 3DP fabric with heat wicking ability. Only because of the compatibility of 3DP technology it was possible to use a mixture of PVA and boron nitrate as print material that excelled the product’s thermal conductivity [258, 260]. NASA engineers from Jet Propulsion Laboratory (JPL) have developed a 3DP fabric prototype for the astronauts, which is flexible and durable, in the form of connected metallic tiles [261].

8.3 Complete garment structure

The use of 3DP in the fashion industry is gaining traction as it provides a wide range of possibilities [262–264]. Dutch industrial designer Jiri Evenhuis and Finnish conceptual artist-designer Jane Kyttanen were the first to create a fully functional 3DP dress named ‘Black Drape Dress’ (see **figure 24**) [265]. They were thinking about the troubles of travelers in carrying luggage and wanted to create clothes, bags and accessories which can be downloaded and reproduced at any location using 3D printers. They named the project ‘Lost Luggage’, and the Black Drape Dress is a part of this project. Thousands of 3DP individual particles were looped together to create this flexible dress [266].

Figure 24. Black Drape dress [265, 267] (waiting for permission)

There was a long gap after the Black Drape Dress, but from the beginning of the 2010s, many new creative projects using 3DP technology popped up on numbers of fashion shows [264]. Iris van Harpen was one of the frontline adopters of 3DP techniques and an influential designer who has been developing and presenting 3DP dresses on haute couture fashion shows since 2010 [268]. In 2010, she presented her first 3DP dress as a part of the Crystallisation collection created using SLS technology. The dress was printed from white polyamide, and it recalls the way that limestone deposits form shells [269]. Thus far, she has shown about 15 unique 3DP dresses on different fashion shows [270]. Three of them are shown in the **figure 25**. Using 3DP techniques, she tried to build conceptual dresses, which embodies very complicated structures and geometries, which would be impossible otherwise [271]. She also tried to push the boundaries to 3DP in terms of flexibility and fabrication for printing textile-like garments [272]. She has collaborated with Neri Oxman from MIT Media Lab [276], Italian architect and professor Niccolo Casas [277], Austrian architect and designer Julia Koerner [278], London based architect Daniel Widrig [279], Belgium-based architect Isaie Bloch [280] and scientist from the Delft University of Technology [281] to build these innovative dresses.

Crystallization Collection-Look 12 [273]

Foliage Dress -Ludi Naturae Collection [274]

Voltage Collection -Black Dress [275]

Figure 25. a) Crystallization Collection-Look 12, [273], **b)** Foliage Dress -Ludi Naturae Collection [274], **c)** Voltage Collection -Black Dress, [275] (Dresses Printed by Iris Van Harpen Permission yet to receive)

Fashion company threeASFOUR has built a legacy of using modern cutting-edge technology with traditional craftsmanship to intersect fashion and art for creating clothing items. 3DP dresses manufactured by them are shown in the **figure 26.** It was founded by three transnational artists named Gabriel Asfour, Angela Donhauser and Adi Gil in 2005 [282]. They explored how to replicate natural morphologies and biological forms and complex geometry in clothing with 3DP. The Bahai dress, the Harmonograph dress, the Oscillation dress, Pangolin dress are some examples of their fine art [283].

a) The Harmonograph Dress [284]

b) The Oscillation Dress [285]

c) The Kinematics Dress [286]

Figure 26. a) *The Harmonograph Dress**,** reused with permission from* [284]*, copyright © 2016 ThreeASFOUR and photo credit: Matt Carasella,* ***b)*** *The Oscillation Dress, reused with permission from* [285]*, copyright © 2016 ThreeASFOUR and photo credit: Ben Gabbe, c) The Kinematics Dress, reused with permission from* [286]*, copyright © 2014 NERVOUS SYSTEM. INC. and photo credit: Steve Marsel Studio.*

Due to the limited printing area, 3DP dresses are generally printed in parts and then assembled. MIT alums Jessica Rosencrantz and Jesse Louis-Rosenberg, founders of Nervous System, wanted to print a dress that will be wearable straight out of the machine and would not require assembly after printing [287]. To achieve this, they created a dress from the 3D scan of the body and then used simulation to fold the dress into a smaller form for printing in a single part [288]. They have printed the Kinematics dress, and the Kinematic Petals dress using this process [288, 289]. A floor-length gown named 'Dive into Me' were also printed in one piece by Malaysian Fashion Designer Melinda Looi and Samuel Canning of Griffith University.

Most of the 3DP dresses are printed on large and expensive industrial printers due to the size of the dresses. Israeli designer Danit Peleg saw that home printers were much cheaper and more accessible and decided to make the dresses for her graduation project using home printers. She designed and printed five dresses (shown in the **figure 27**) of her 'Liberty Leading the People' collection piece by piece and assembled them like a puzzle from home [290]. This collection went viral and showed the potential for applying 3DP technology in the field of fashion.

Figure 27. *Liberty Leading the People Collection by Danit Peleg, Reused with permission from* [291]*, Copyright © 2018 Copyrights [DANIT PELEG]*

This visionary designer touched a milestone by creating a flexuous 3D-printed dress as part of 'The Birth of Venus Collection", which was worn by Amy Purdy as her dance costume (shown in **figure 28 (a)**) at the inaugural ceremony of the Paralympic Games in Rio de Janeiro held in 2016 [292]. She has also opened an online shop from where people can buy jackets of 'The Birth of Venus' collection with some customisation [293]. She dreams of a future where people will be able to print their own clothes at home. In an interview with Erin Winick, Danit Peleg said, "Now I can email you a jacket or a dress but imagine that in a few years, you will be able to download this jacket and easily change the size and design; then print it in a few minutes." [294].

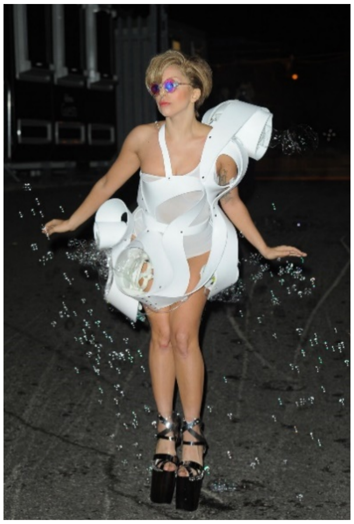
(a) Paralympics Dress - The Birth of Venus Collection [295]

(b) The Parametric Skin Suit - The Liberation Collection [296]

(c) The Pure Nature Suit -The Liberation Collection [296]

Figure 28. a) *Paralympics Dress, Reused with permission from* [295]*, Copyrights © 2016 DANIT PELEG*, ***b)*** *The Parametric Skin Suit, Reused with permission from* [296]*, Copyrights © Julia Daviy,* ***c)*** *The Pure Nature Suit, Reused with permission from* [296]*, Copyrights © Julia Daviy*

Sustainability is a big concern for the textile industry as it is one of the top pollutant-generating industries in the world [297]. Fashion designer Julia Daviy, who is also an ecologist and clean technology industry manager, thought that 3DP dresses could reduce the environmental footprint of fashion based products [298]. Later, she created the Liberation Collection (shown in the **figure 28 (b), 28 (c)**), a 9-piece collection of 3DP dresses, which won the 2019 Eluxe Awards, the world's largest contest of sustainable products. The dresses of this collection were flexible, comfortable and more importantly everyday wearable, something you can wear at reception or event rather than only on-ramps. She has also patented her method of creating zero-waste dress on large-format printers in the USA. She thinks that the revolution of 3DP will save the women worker from the exploitation of mass production system and will empower them by allowing to create unique fashions with affordable 3DP equipment [299].



a. Lady Gaga's Anemone dress [300]

b. The Synapse Dress [301]

c. Caress of the Gaze [302]

Figure 29. *Smart tech integrated 3DP dresses* ***a)*** *Lady Gaga's Anemone dress (permission yet to receive),* ***b)*** *The synapse dress, Reused with permission from* [301]*, Copyrights © 2014 Anouk Wipprecht FashionTech,* ***c)*** *Caress of the Gaze, Reused with permission from* [302] *Image courtesy © 2016 Behnaz Farahi, Photographer: Elena Kulikova.*

3DP has also enabled designers to integrate smart technology into wearable dresses, and Lady Gaga was the first to wear such a dress in public (shown in **fig 29 (a)**). She wore Studio XO's 3DP bubble-blowing dress named Anemone at the launch of her album ARTPOP [300]. Dutch Fashion Tech Designer Anouk Wipprecht is a pioneer and has designed dresses that interacts with the surroundings (shown in **figure 29 (b)**). Her Synapse dress, equipped with an EKG, a proximity sensor and a camera, gives the wearer extrasensory capabilities that react to both her physical and social environments. If another subject moves in too close to the wearer, the dress creates a super bright glow that tells the subject to "back off" [301]. Caress of the Gaze is another example of quintessential integration of smart technology and wearable 3DP dress (shown in **figure 29 (c)**), designed by Iranian-American architect Behnaz Farahi, that detects people's gaze using computer vision technologies and moves parts of the dress using actuation systems [302].

The Table 8 below accumulates most of the 3DP dress with their features, name of used 3DP technique, materials and designers.

Table 8: 3DP dresses with their designers, fabrication year, materials, 3DP techniques and special features

Dress Name	Designers	Year	Materials	3DP Technique	Features	Reference
Black Drape Dress	Jiri Evenhuis, Janne Kyttanen	2000	Polyamide	SLS	Fully functional, flexible and breathable	[304]
Crystallization Collection (Look 12)	Iris van Herpen, Daniel Widrig, Materialise	2010	Polyamide	SLS	Rigid, inspired by the transformation of liquid into crystals	[305]
Escapism Collection (Look 2)	Iris van Herpen, Daniel Widrig, Materialise	2011	Polyamide	SLS	lightweight, flexible and lace like structures produced without any needle or thread	[306]
Skeleton Dress	Iris van Herpen, Isaïe Bloch, Materialise	2011	Polyamide	SLS	Rigid dress; the design consists of stylized ribcage, spine motif and pelvic bone	[307]
Hybrid Holism (Look 10)	Iris van Herpen, Julia Körner, Materialise	2012	Acrylonitrile Resin	SLA	Rigid dress, incorporates complex geometrical structures	[307]
Cathedral dress	Iris van Herpen, Isaïe Bloch, Materialise	2013	Polyamide	SLS	Rigid dress, looks like a sculpture of wood	[308]
Anthozoa: Cape & Skirt	Iris van Herpen, Neri Oxman, Stratasys	2013	Polyeurethane Rubber & Acrylic	PolyJet	allowed both hard and soft materials to be printed in a single build	[309, 310]
Voltage Collection (Black Dress)	Iris van Herpen, Julia Körner, Materialise	2013	TPU 92A-1	SLS	Fully flexible dress, developed by superimposing multiple layers of thin woven lines which flows across the body like a woven web	[275]
Wilderness Embodied Collection (Hybrid Dress)	Iris van Herpen, Iris van Herpen, Isaïe Bloch, Materialise	2013	Clear Liquid Resin	SLA	Rigid dress, produced by over-molding 3DP transparent bone-like structures in silicon	[311]

Biopiracy Collection (Look 20)	Iris van Herpen, Julia Körner, Materialise	2014	TPU 92A-1	SLS	Fully flexible dress, moves freely with a glossy sheen	[312]
Magnetic Motion	Iris van Herpen, Niccolo Casas, 3D Systems	2014	Accura ClearVue	SLA	Transparent dress, high level details, covered in crystalline formations	[313]
Hacking Infinity	Iris van Herpen, Niccolo Casas, 3D Systems	2015	Accura ClearVue	SLA	Combination of motion and complexity, 6556 unique individual components continuously react to the body's movement.	[314]
Magma dresses 1 (Lucid Collection)	Iris van Herpen, Niccolo Casas, Materialise	2016	Polyamide	-	Flexible dress, created by stitching together 5000 individual 3DP elements	[315]
Magma dresses 2 (Lucid Collection)	Iris van Herpen, Niccolo Casas, Materialise	2016	TPU 92A-1	-	Flexible dress, formed "fine web" combining flexible TPU printing with polyamide printing	[316]
Foliage dress (Ludi Naturae Collection)	Iris van Herpen, TU Delft	2018	thermosetting polymers, tulle fabric	PolyJet	Flexible dress, tulle fabric was inserted after printing several layers, followed by printing of the next layers on top	[274]
Liberty Leading the People Collection	Danit Peleg	2015	FilaFlex by Recreus	FDM	Flexible dresses, printed by home printers	[290]
Paralympics Dress (The Birth of Venus Collection)	Danit Peleg, Gerber Technology	2016	FilaFlex by Recreus	FDM	Flexible, comfortable jackets that moves freely	[295]
Liberation Collection	Julia Daviy	2018	70A TPE, Flexible Resin	FDM, SLA	flexible, comfortable, fashionable, innovative & everyday wearable	[317]
Bahai Dress (MER KA BA collection)	threeASFOUR, Bradley Rothenberg, Materialise	2013	Resin	FDM	Rigid, Flat Pattern pieces of Fractal interlocking weave	[282]
Harmonograph Dress	threeASFOUR, Travis Fitch, Stratasys	2016	Agilus30, VeroBlack	PolyJet	Flexible, durable, made of interwoven structure, circle of the spiral follows geometry of Fibonacci sequence	[284]

Oscillation Dress	threeASFOUR, Travis Fitch	2016	Agilus30, VeroCyan, VeroWhite	PolyJet	Flexible, made of interwoven, interlocked structures derived from vibrational & frequency geometry	[285, 318]
Pangolin Dress	threeASFOUR, Travis Fitch, Stratasys	2016	Agilus30, VeroBlack	PolyJet	Flexible, durable, comprised of 14 pattern pieces, made of interlocking weaves	[284]
Kinematics Dress	Jessica Rosenkrantz, Jesse Louis-Rosenberg, Shapeways	2014	Nylon	SLS	Breathable, stretchable, made of triangular panels interconnected by hinges, can move and flow, printed in one piece through folding	[288, 319]
Kinematic Petal Dress	Jessica Rosenkrantz, Jesse Louis-Rosenberg, Shapeways	2016	Nylon	SLS	Flexible, made by interconnecting 1600 unique pieces by more than 2600 hinges, aggregated rigid components react as continuous textile, printed in one piece through folding	[289]
inBloom Dress	Lim Kae Woei and Elena Low Lee Wei (XYZ Workshop)	2014	Flexible PLA Filament	FDM	longest 100% desktop 3DP dress, created from a primary mesh of a geometric floral motif, made of 191 panels	[320]
Loom Dress	Maria Alejandra Mora Sanchez	2018	TPU	FFF	a flexible, expandable, adapts to body change, ready-to-ware, comfortable	[321]
Dive into Me	Melinda Looi, Samuel Canning	2013	Polyamide	SLS	Floor-length gown with more than 5,000 crystals molded into 3DP ‘fabric’, printed in single part	[322, 323]
Verlan	Francis Bitonti, MakerBot	2013	MakerBot Flexible Filament	FDM	referenced muscle fibres, veins and arteries to an inside-out body	[324]
Bristle Dress	Francis Bitonti, MakerBot	2014	MakerBot Flexible & Natural PLA Filament	FDM	The top of the dress is big volume, cloud-like translucent haze and the skirt suggests lace-like origami.	[325]
Dita’s Gown	Francis Bitonti, Michael Schmidt Studios, Shapeways	2013	Nylon	SLS	Flows with the body, nearly 3000 unique articulated joints detailed with 13,000 black Swarovski crystals	[326, 327]
Snow Queen	Victoria's Secret, Bradley Rothenberg (Shapeways)	2013	Nylon	SLS	Rigid, festooned with thousands of Swarovski crystals	[328]
Smock Corset	Julia Koerner, Marina Hoermanseder	2015	Liquid Resin	SLA	Historic corset design with a spectacular 21st century twist	[329]
Sporophyte Collection	Julia Koerner, Stratasys	2015	TangoBlack Plus and VeroBlack	PolyJet	Inspired by natural structures found in fungi and kelp, allows for flexibility via a combination of rigid and rubber-like structures	[330]
Néobaroque Collection	Pia Hinze	2013	Nylon 12	SLS	Rigid, organic shapes like flourishes were printed in parts and then assembled	[331]

Wanderers collection	Neri Oxman, Christoph Bader, Dominik Kolb	2014	VeroCyan, VeroClear, VeroMagenta, VeroYellow	PolyJet	3DP wearable capillaries are infused with synthetically engineered microorganisms to make the hostile habitable and the deadly alive. They are designed to interact with a specific environment and generate sufficient quantities of biomass, water, air and light necessary for sustaining life from elements that are found in the atmosphere	[332]
Lady Gaga's Anemone dress	Benjamin Males, Studio XO	2013	Polymer Resin	SLA	Rigid, blows large and small bubbles	[48, 300]
Spider Dress 2.0	Anouk Wipprecht, Philip H. Wilck	2015	Nylon 12	SLS	equipped with an Intel Edison chip that reads biosignals to defend the wearer's personal space	[333]
Hard Core Vein 2.0	Maartje Dijkstra, Creative Industries Fund NL	2014	Transparent PET filament	-	Made of tubes filled with ink that pump with beats of music, "like blood through a vein on a heartbeat"	[334]
Synapse Dress	Anouk Wipprecht, Niccolo Casas, Materialise & Intel Edison	2014	TPU 92 A-1	SLS	flexible, comfortable and reads body signals, and proximity of other people to respond in an intuitive manner.	[301]
Smoke Dress	Anouk Wipprecht, Niccolo Casas, Materialise & Intel Edison	2013	TPU 92 A-1	SLS	Demonstrates a dialogue between the wearer and the environment by producing a smoke veil when it is interrupted by someone else	[335]
Caress of the Gaze	Behnaz Farahi	2015	Shore 60 Black, Vero White	PolyJet	Flexible, responds to the gaze of others by moving the gazed parts of the dress	[302]

8.4 PPE

Works are being conducted to uncover the effectiveness of 3DP as a fabricating method for protective functional element on textiles. These protective parts should stall hazards like impact, penetration compression, etc. Such 3DP protective gears will enable us to avoid the discomfort and uneasiness associated with currently used reinforced plastic and polyurethane foam combination [2]. Park and Lee [4] developed a mesh pad using a flexible Thermoplastic Polyurethane (TPU) and FDM technique to protect the human body against fall impact.

Further, a protective face mask was designed and developed via successful implementation of 3D imaging and 3DP. The researchers developed the reusable protective mask for the face and a membrane with filtration functionality utilising 3DP polyamide composite [336]. Textile integrated 3DP back protector was developed to eliminate the pressure over the shoulder while caring heavy loads. Knee protector was manufactured by imprinting TPU2-86A as printing paste onto polyester knitted surface [174]. Orthopedic devices to aid in the reformation of the knee injuries are created using 3DP method printed on a flat textile knitted surface comprised of polyamide and elastane [29]. 3DP techniques such as SLS, SLA are used to prepare textile-like structures like bikinis or shoes [231, 337]The **table 9** summarises the protective gears that have been developed using 3DP technology.

Table 9: Different protective gears developed with 3DP technology

Protective Gear	3DP Component	Materials	3DP Technique	Application Area	Reference
Protective Face Mask	Reusable mask and filter membrane	Polyamide composite	Selective Laser Sintering (SLS)	Human face	[336]
Personal Protective Gear	Knee and Crotch protective components	Thermoplastic polyurethane	Additive Manufacturing (AM, Desktop 3DP)	Knee, hip joint, elbow, Crotch protector etc.	[2]
Protective Pads	Fall impact protection pad	Thermoplastic polyurethane (NinjaFlex)	Fused Deposition Modelling (FDM)	Human body parts vulnerable to fall impact	[4]
Safety Protective Clothing	Elbow and knee protective 3D shaped component	Shape memory thermoplastic polyurethane	Fused Deposition Modelling (FDM)	Elbow, Knee, etc.	[179]

.

8.5 Sensor, electrode, conductor, actuator

Textile materials are nowadays thriving towards a smarter and intelligent approach by integrating novel functionalities, which are able to give real-time feedback. 3DP in this regard has taken a pivotal role since computer sketched objects constructed by 3D printers have the leverage of substantial design flexibility and boosted performance [208]. Multipart symmetrical designs and integration of multi-functional end-user devices were triggered by 3DP [338]. Multi-functionality means the introduction of additional functionality, which are imperative for attaining adaptability, weight reduction, self-sustainability and autonomy regardless of the basic shape [180, 339]

It is worth noting that conductive materials are vital attributes of 3DP operative materials. There has been a conspicuous development in manufacturing 3DP electrically conductive object with complex geometry and multiple functions [340]. Unlike other conventional methods, 3DP of conductive polymer nanocomposites (i.e. carbon nanotubes, graphene nanosheets etc.) does not require any mould to create. It can work decisively based on mere speculation of the surface geometry of the object. At the same time, it renders excellent conductivity property. CNC (conductive nanocomposite) based electrically conductive scaffold microstructures with different constructional parameters (i.e. the thickness of scaffolds, configuration patterns, filament diameter and, inter- filament spacing) were assembled by solvent-cast 3D printing method (SC3DP), which can be later used as liquid sensors [209]. Furthermore, 3DP multifunctional nanocomposite structure can also be used for the application of strain sensor [341], lab-on-chips [342], TRGO (thermally reduced graphene oxide) electrodes [343], titanium interdigitated electrodes [344] etc. Another study of Ambrosi et al. [345] showed that metal 3D printing with a selective laser melting based machine used for forging stainless steel electrodes, which can be maneuvered as a platform for pH sensor application.

The Table 10 lists the recently developed 3DP applications in the field of sensors, electrodes, microelectronics, capacitors, etc.

Table 10: Some recently 3DP substrates for application in the field of electrodes and microelectronics

Application Type	Material Used	3DP Technique	Application/advantage	reference
Strain sensor	Single-walled carbon nanotube composite(SWCNT)	Ultraviolet facilitated direct-write (UV-DW)	Sensors are very susceptible to minute mechanical interferences, which is very desirable. Freestanding geometry of the sensors has the potential to truncate the effect of an	[341]

			unprecedented stimulant on the result	
Liquid sensor	PLA/MWCNT (Multi-wall carbon nanocomposite)	SC3DP	Relatively High electrical conductivity. Excellent sensitivity even for a short dipping	[346]
TRGO (thermally reduced graphene oxide) electrodes	GO (graphene oxide)-letter converted into TRGO ink through HPH (high-pressure homogenization)	3D micro extrusion	Devoid of binder and surfactant-free electrodes. Tolerance of high viscosity. Graphene-based EC(Electrochemical capacitor) gives a cutting-edge performance in comparison to electrolytic capacitors	[343]
Titanium interdigitated electrodes	Ti–6AI–4 V metal powder	SLM (Selective laser Melting)	Micro-super capacitors based on this interdigitated structure have high energy storage capacity for the additional third dimension.	[344]
Biosensors	Conductive hydrogels or conductive hydrogels precursor	3D bio plotting/light-based printing, stereolithograph y (SL/SLA), direct laser writing (DLW) or DLP/Ink-Jet printing	Tissue engineering, wearable electronics, stability of the shape of the printed structure.	[347]
Nanocomposite supercapacitors, strain gauge sensor	Solution of photopolymers filled with titanium and silver nanoparticles	Inkjet printing	Enhanced mechanical property, electrical conductivity, thermal stability and gas barrier properties.	[348]
Flow sensors	Hydrogel nanocomposites filled with polydiacetylene nanoparticles	Dynamic optical projection stereolithograph y (DOPSL)	Enable rapid, low cost and customized fabrication.	[349]
Electronic sensors	Thermoplastics (PLA or ABS) filled with hydroxyapatite, nano clay or Nanocrystalline	Fused deposition modelling (FDM)	Single build method devoid of any complex and expensive materials.	[350]
Microelectronics , antennas	Conductive ink of silver nanoparticles,	Conformal 3DP (C-3DP)	Potential for order of magnitude augmentation	[351]

	photopolymers incorporated with nanotubes.		over basic monopole designs.	
sensing applications, MEMS (micro-electromechanical system), microelectronics	Photopolymers (urethane, epoxy) filled with nanotubes	Ultraviolet 3D printing	Creation of complex and miniature geometry with enhanced mechanical, thermal, optical property.	[352–355]
Hollow capacitive sensor, smart structure with shape memory effect, stretchable spring circuits	Photocurable resin with MWCNTs	Digital light-based 3D printing(DLP)	Layers can be formed rapidly in this method, potential to reshape the final properties.	[143]
Capacitive sensor	Ionically conductive PAAm-PEGDA(polyacrylamide - poly ethylene glycol diacrylate) hydrogels.	Digital light-based 3D printing (DLB3DP)	Sensing both pressure and strain, high sensitivity, surface quality require no additional supporting structure.	[356]
Solid-state flexible super capacitors	Graphene Oxide(GO)	Screen printing	Excellent mechanical stoutness, avoid the inconvenience linked to fabricating devices with conductive yarn	[357]
Capacitive soft strain sensor (CS3)	Non-volatile conductive ionic fluid modified soft silicone elastomer	Multicore-shell fibre printing	Sensors with meticulous and hysteresis-free dispatching in both stable and unstable operating conditions	[358]

However, multifunctional structures are required to involve more than one material to sync sensing and actuating property together. But it compromises the aspects of assembly, processing, compatibility etc. Biocompatible shape memory polymers PLA and polyethylene adipate (PEA) were added with BT (Barium Titanate Nanoparticles), having piezoelectric effects by solvent evaporation assisted direct-write (DW) 3D printing technique. The study of Bodkhe et al. [180] concluded that PEA, as a material, does not have any effect in the process, and both sensing and actuation can be achieved by PLA/BT integration alone without the use of PEA through 3D printing. Polymer nanocomposites (PNC) integrated with conductive nanofillers, such as CNT or graphene, were also used for building materials with different multifunctional properties (electrical conductivity, thermal conductivity etc.) via desktop 3D printing [208]. Furthermore, the composite of boron nitride(BN)/Polyvinyl alcohol(PVA), fabricated through 3D printing technique, produced 1.56 and 2.22 time higher thermal conductivity than PVA fabrics and cotton fabrics, respectively [206]. The **figure 30** shows some application of attachment of 3DP wearable electronic devices.

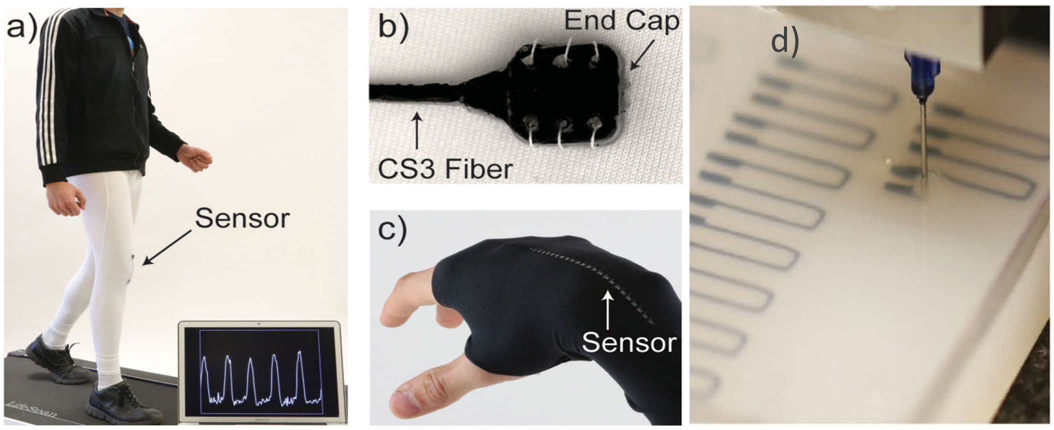


Figure 30 a) *3D Printed capacitive soft strain sensors integrated to fabric across the knee via* ***b)*** *sewing* ***c)*** *weaving, Reused with permission from* [358]*, Copyright © 2015, WILEY-VCH.* ***d)*** *embedded 3D printing for the soft strain sensors, Reused with permission from* [359]*, Copyright © 2020 Elsevier B.V.*

In a bid to create smart textiles that can interact with the surrounding, electronic sensors and actuator can be integrated by conventional textile technology like sewing, embroidery, knitting, coating, braiding, weaving etc. However, none of them could hardly yield to the threshold performance and hence produce more or less inaccurate result [352]. On the contrary, 3DP technology showed very good potential for use in textile-integrated circuit paths [352]. 3DP has been utilised to augment a group of sensors that can be mounted on a textile for sensing different mechanical parameters [360, 361]. By this method, inserting a sensor into printed shape was done seamlessly, and the result was impeccable [338]. Moreover, 3D direct-write dispensing is a protean additive manufacturing technique that has given new impetus for the printing of convoluted geometries with impeccable accuracy, enabling the erection of conductors and antennas on the textile substrate [362]. These geometric shapes can be modified at full discretion because, as previously stated, no die or mould is required. The fabrication and wireless performance of textile-integrated passive UHF RFID (radio frequency identification) tags with 3D printed stretchable antennas have also been studied [339, 363]. The result revealed that 3D printed joint has higher ascendancy ranges and thus superior wireless performance than epoxy-glued and embroidered joint. To make more innovative, responsive smart products, energy stored in a 3DP textile can be used, including the concept of 4D textiles, that will find applications in a broad range of industrial sectors in the upcoming future [198].

There have been numerous study of 3D printing by traditional filaments such as polylactic acid (PLA), acrylonitrile butadiene styrene (ABS), nylon [45, 68, 364] . Unorthodoxly conducted 3DP of electrically conductive composite special filament can act as a bridging component between textile conduction lines and electrical components [365]. The conductive filament used to have a higher degree affinity for polyester knitted textile compared to woven fabric.

FBG (Fiber Bragg grating) sensor was implanted into a 3D printed ring by FDM method for overseeing different physical aspects of the human bodies by apprehending tensile deformation [338]. By this method, the function of the FBG sensor was culminated to the highest point of excellence. The 3DP belt ring is very pliant in nature and enables secure body joints along with the FBG sensor. The whole design can even be customized by FDM technology which ensures compatibility and an error-free measurement.

Unlike conventional printing, 3DP can produce electrodes of different geometries: such as helical, gauge etc. Electrodes produced through 3DP offer robustness, high-throughput performance and better precision, which in terms offer better sensing property [340].

3DP has also paved the way for the production of actuators. Conventional actuators have been superseded by soft actuators due to its amplified response for the deformation of actuator material [366]. But the fabrication of this material is very laborious. Instead, 3DP is used in this aspect which consolidates all the components into a unified structure and curtail the necessity for any external components [367]. In this way, 3DP is exploiting in all realms of functional electronic devices.

9. Test methods and standards

Some international standards are there to be followed for testing the 3DP for textile and fashion. To have a perfect result and validation, it is essential to follow the test methods strictly and unconditionally, according to internationally recognised organisations. The International Organisation for Standardization (ISO) is such a non-public, independent, international organisation that brings experts together to partake knowledge, support innovation, and provide solutions to global challenges [368]. Scientists and profressionals all over the world apply these ISO standards and test methods on a regular basis.

As for example, ISO 6133:2015 is used by Meyer et al. [238] to determine adhesion strength between textile fabrics & different types of polymer coating substances. The influence of 3DP platform temperature and fabric properties on the stress, strain, and deformation is studied by Eutionnat-Diffo et al. [30]. They examined the tensile and elongation at break according to ISO 13934-1:2013 method. They also applied the washing test in a domestic washing machine following the standard ISO 6330:2012. Even they measure the thickness of 3DP fabrics with a micrometre KES-FB3 and a thickness gauge according to ISO 5084:1996. The compression testing is measured at a compressive velocity of 1mm/in with 24KN proof load and 30KN rod cell in a universal tester by Lee et al. [2] with a reference of ISO 604:2002. Korger et al. [174] analysed abrasion resistance with Martindale test on wool fabrics with 12 KPa pressure up to 40000 cycles according to the international standard ISO 12947-2:2016. In the same particular article, the fastness to washing is examined according to ISO 15797:2017 up to 50 cycles with 60°C line drying and the adhesion test after washing is performed by using an Instron testing device based on ISO 2411:2017. With a separation rate of 100mm/min, other adhesion tests are done by Razieh et al. [369] according to test method ISO 11339:2010 by using a Zwick or Z010 tensile tester. The flexural modulus and tensile strength are measured by Fafenrot et al. [370] according to ISO 178 and ISO 527-1:2019, respectively, using Sauter universal testing instrument. The ISO 527-3:2018 was used by Szykiedans and Credo [216] for doing a tensile test with some different type of materials using the MTS Bionix 270 test system.

The American Society for Testing and Materials, shortly ASTM, is another international standard organisation that contributes towards research, production, environment safety of a wide range of materials, products, systems, and services with more than 12000 standards globally [371]. Their standards are also very popular, and numerous examples of application are available.

Lipton and Lipson [246] did compression tests with 3DP samples by compressing and releasing at a rate of 12mm/min along the Z-axis of print according to ASTM D575 –91. The material flow rate for different amounts of virgin polymers has been tested by Kumar et al. (2019) [197] following ASTM D1238 international standard maintaining 2.16 kg of load and 190°C temperature. According to ASTM D5034, Mpofu et al. [175] carried out the tensile test using Testometric Micro 500 model tensile tester (Belgium) with a speed of 100mm/min. The traditional hook and loop material testing is done by Narula et al. [198] according to ASTM D5170, where the average peak loads are the parameters of material evaluation. Siewhui Chong et al. [205] did a water absorption test of recycled high-density polyethylene as printing substances based on ASTM D570. The international standard ASTM D3763 and ASTM D6110 are applied by Kabir et al. [153] to test the drop-weight impact system and the Charpy Izod impact assessment of unnotched samples, respectively. The important mechanical property flexural strength of 3DP material specimens are tested by Weng et al. [72] as a reference of ASTM D790-03.

The **table 11** illustrates the accumulation of such testing methods of international standards and their contribution towards the 3DP on textiles.

Table 11: Test methods and international standards associated with various 3DP testing

Standard	Title	Objective	Scope for 3DP on textile	Reference
ISO Standards				
ISO 6133:2015	Rubber and plastics – Analysis of multi-peak traces obtained in determinations of tear strength and adhesion strength	Determine the tear strength and adhesion strength of vulcanized rubber or fabric coated with or attached to rubber or plastics. The standard calculates the median and range of peak value from a graphical plot of force versus time. It ensures more uniformity in the evaluation and presentation of test results.	The adhesion depends on the inter-fibre friction between yarn and the polymer substances. By this standard, the adhesion strength of some rubber or plastic materials on a specific textile fibre could be determined according to the application of the end product.	[238, 372]
ISO 13934-1:2013	Textiles – Tensile properties of fabrics Part 1: Determination of maximum force and elongation at maximum force using the strip method	The maximum force and elongation at the maximum force of textile fabrics are determined in this standard by using the strip method. Applicable to woven fabrics as well as stretched fabrics with elastomeric fibre imparting with mechanical or chemical treatment. Coated fabrics, nonwovens geotextiles, textile-glass woven fabrics, fabrics inherent carbon fibres, or polyolefin tape yarns are not applicable in this standard.	The standard assists to optimize the theoretical & statistical model of fabric properties and some other factors like printing temperatures on stress, strain, and deformation of printing materials deposited on textile fabric through the 3DP process.	[30, 373]
ISO 12947-2:2016	Textiles – Determination of the abrasion resistance of fabrics by the Martindale method – Part 2: determination of specimen breakdown	Specifies the procedure of identifying the specimen breakdown (end-point of the test) by inspection at fixed intervals. All textile fabrics, including nonwoven and specifiers having low wear life, are applicable here. On the other hand, it does not apply to coated fabrics, including laminated fabrics.	Applying the Martindale test with a specific amount of rubbing cycles determines the loss of thickness of different printing substances. Thus, proper materials could be selected under the correct specification of 3DP textile products.	[174, 374]
ISO 15797:2017	Textiles – Industrial washing and finishing procedures for	For testing colour characteristics, dimensional stability, seam puckering, creasing, pilling, and visual aspects, this standard has been used. It uses defined intermediate scale equipment and exacts test procedures that could be used for the	In order to introduce new functional development in the workwear sector, fastness to washing & wash resistance	[174, 375]

	testing of workwear	evaluation of workwear intended to be laundered industrially.	is a demanding requirement for the 3DP process.	
ISO 2411:2017	Rubber- or plastics-coated fabrics – Determination of coating adhesion	The standard specifies a method of determining the coating adhesion strength of coated fabrics. Due to inadequate adhesion strength, delamination may occur and fails the product.	Resultant form-locking connection & effective polar interaction between yarn and print polymers contribute to the amount of adhesion force.	[174, 376]
ISO 11339:2010	Adhesives – T-peel test for flexible-to-flexible bonded assemblies	To determine the peel strength of an adhesive, this international standard is used. It measures the peeling force of a 'T' shaped bonded assembly of two flexible adherents. Metal adherents and flexible adherents may use this method.	In order to explain polymer-to-polymer adhesion, different types of theories can be applied under different conditions between two flexible adherents in this specific standard.	[369, 377]
ISO 527-3 :2018	Plastics – Determination of tensile properties – Part 3: Test conditions for films and sheets	This standard specifies the condition to determine the tensile properties of plastic films or sheets less than 1 mm thick. The method is not suitable for cellular materials and textile fibre reinforced plastics.	The tensile strength of various filaments of different companies could be examined. The method can determine the delamination force of the fused layer and the force needed to break the partially fused layer inside.	[216, 378]
ISO 6330:2012	Textiles – Domestic washing and drying procedures for textile testing	These washing and drying testing procedures are applicable for textile fabrics, garments, or other textile articles of appropriate combinations. The standard also specifies the reference detergents and ballasts.	After implementing this international washing procedure, some important parameters like tensile resistance, stress at rupture &durability could be checked for the feasibility of the 3DP process.	[30, 379]
ISO 5084:1996	Textiles – Determination of thickness of textiles and textile products	The standard measures the thickness under a specified pressure. It does not apply to textile floor coverings, nonwovens, geotextiles, and coated fabrics.	The stress, strain, tensile force, and other related properties depend on the thickness of the textile fabric. This is the reason for executing the international standard.	[30, 380]
ISO 604:2002	Plastics – Determination of compressive properties	Here the compressive properties have been determined under some defined conditions like a standard test specimen and a range of test speed. The length of the specimen has to be adjusted to prevent buckling under load.	The test determines compressive behaviour, compressive strength, compressive modulus, and the compressive stress-strain relationship of 3DP textiles. The compressive strength is related to the infill ratio, tensile & shock absorption properties.	[2, 381]
ISO 527-1:2019	Plastics – Determination of tensile properties – Part 1: General principles	The methods are used to check the tensile behaviour of the test specimens like tensile strength, tensile modulus, and other aspects of the stress/strain relationship of plastics and plastic composites under defined conditions.	The methods of determining tensile properties are suitable for rigid, semi-rigid moulding, extrusion & cast thermoplastic material, filled & reinforced compounds, whereas not suitable for rigid cellular material.	[370, 382]
ASTM Standards				

ASTM D575 – 91(2018)	Standard Test Method for Rubber Properties in Compression	To compare the stiffness of rubber materials in compression, this standard is used. The legal aids to develop rubber materials for the compressive application.	This mechanical testing in 3DP shows the behaviour of the composites according to the iso-stress model while in compression.	[246, 383]
ASTM D1238	Standard Test Method for Melt Flow Rates of Thermoplastics by Extrusion Plastometer	The test particularly uses for quality control tests for thermoplastics. It serves to indicate the uniformity of the flow rate of the polymer.	The Material Flow Rate has been tested in 3DP for different proportions of reinforcement & virgin polymers by maintaining standard conditions.	[197, 384]
ASTM D5034	Standard Test Method for Breaking Strength and Elongation of Textile Fabrics(Grab Test)	To determine breaking force and elongation for acceptance testing of commercial shipments of most woven and nonwoven fabrics in trade.	There is an effect of extrusion speed, temperature as well as fill density of 3DP substances on tensile strength testing.	[175, 385]
ASTM D5170	Standard Test Method for Peel Strength("T" Method) of Hook and Loop Touch Fasteners	This test method determines the measurement of the peel strength of hook and loop touch fasteners using a tensile testing machine recording constant-rate-of-extension.	The 3DP material could be evaluated in terms of the average peak load long with the 180°delamination test. The inch-pound units are used as standard.	[198, 386]
ASTM D570	Standard Test Method for Water Absorption of Plastics	It covers the determination of the relative rate of absorption of water by all types of plastics (cast, hot/cold moulded, etc.) when immersed.	The moisture content of printing material is related to properties like electric insulation, dielectric losses, mechanical strength, appearance & dimensions.	[205, 387]
ASTM D3763	Standard Test Method for High-Speed Puncture Properties of Plastics Using Load and Displacement Sensors	They are designed to provide load versus deformation response of plastics under essentially multi-axial deformation conditions at impact velocities.	Assist in determining puncture properties of rigid 3DP substances over a range of test velocities, thus appropriate in engineering design as well.	[153, 388]
ASTM D6110	Standard Testing Method for Determining the Charpy Impact Resistance of Notched	The resistance of plastics to breakage by flexural shock is determined as indicated by the energy extracted from standardizing pendulum-type hammers, mounted in machines, in breaking standard specimens with one pendulum swing.	Energy losses due to fracture propagation, vibration, friction between the striking nose and the specimen have the potential to become	[153, 389]

	Specimens of Plastics		significant while testing with 3DP material.	
ASTM D790-03	Standard Test Methods for Flexural Properties of Unreinforced and Reinforced Plastics and Electrical Insulating Materials	Determination of flexural properties of unreinforced and reinforced polymer substances, as well as high modulus composites and electrically insulating polymer, moulded or cut from sheets, plates, or moulded shapes.	This flexural property testing method is applied for both rigid and semi-rigid material whereas not applied for materials that do not break within the 5% strain limit.	[72, 390]

10. Manufacturing parameters

The expectations from 3DP products include superior quality, greater productivity, reduced cost and shorter lead time [391]. The properties and behaviours of 3DP parts can be affected by process conditions and parameters to a greater extent than the characteristics of raw materials [32]. Various 3D printers are being employed in manufacturing 3D shapes related to the textiles. Among them, FDM and SLA are more popular than SLS and polyjet modelling (PJM). Grothe, Brockhagen and Storck [172] states the reason behind this is higher cost as well as the engagement of high energy laser power in the latter methods. In the case of FDM, the shape and geometry of the print and mechanical properties [7] are influential drivers of the final product properties. Good mechanical property is a must to ensure durability in-service lifespan as well as operational demand [230]. Mainly the manufacturing conditions and physicochemical properties of the printing materials influence the characteristics of printed parts [30]. The important process parametersinclude deposition speed, layer thickness and flow rate [392]. Sood, Ohdar and Mahapatra [393] explains the effect of five essential processes parameters, i.e. layer orientation, thickness, raster width, angle and air gap on flexural, impact and tensile strength of 3DP part. Qureshi *et al.* [394] highlighted a comprehensive catalogue of 13 controllable process parameters that can influence the mechanical characteristics of the printed part. They utilised a design scalability technique called Taguchi's design of experiment (DOE) method. The FDM extrusion parameters, i.e. melt pressure, maximum extrusion force and minimum extrusion force, are closely related to the dimension and surface morphology of the printed part [395]. A study conducted by Caulfield et al. [396] displayed the impact of scan line distance, speed of laser beam, laser power energy density, etc., on mechanical & physical behaviour of polyamide printed part using the SLS printing technique. Light intensity, printing speed, interface amount, curing time (duration of exposure to light), raw material concentration and layer thickness are important parameters for DLP 3DP technology [147].

Furthermore, it is possible to introduce a wide range of mechanical modifications while working with photopolymers [397]. Mohamed et al. [391] mentioned some general impacting factors of the FDM technique. Those have been depicted in the **figure 31.** Researchers also use different optimising tools to study the impact of process parameters on printed part behaviour as presented in the **Table 12.**

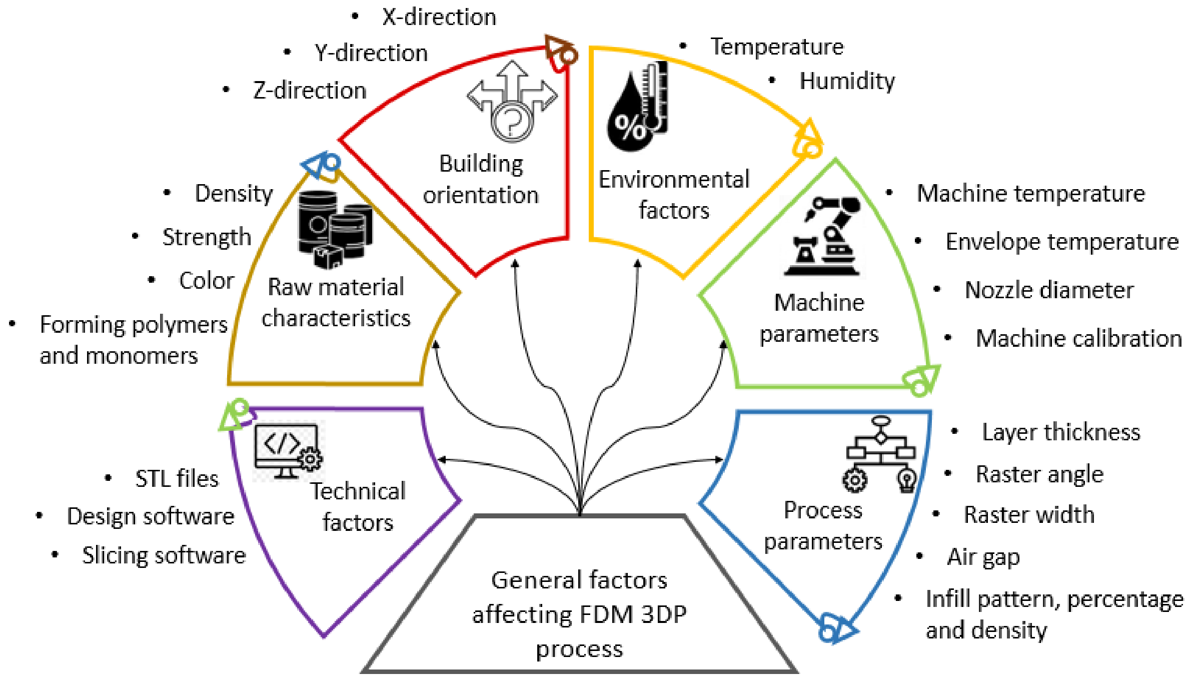


Figure 31. *General factors impacting final 3DP part manufactured by FDM technique, Recreated with permission from [391] Copyright © 2015, Shanghai University and Springer-Verlag Berlin Heidelberg.*

Table 12: Different optimisation techniques to determine optimum FDM process parameters

Observed printed part behaviour	Process parameter	Optimisation technique	Reference
Dimensional accuracy	Build orientation, raster angle, layer thickness, the width of the print, air gap, extrusion and filling speed.	Grey taguchi method, Grey relational grade (GRD), Artificial neural network (ANN), Fuzzy logic.	[398–401]
Surface roughness	Deposition speed, layer thickness, print width, raster angle, air gap, model temperature, filling style.	Taguchi's design matrix, Analysis of variance (ANOVA), the signal to noise ratio (S/N), Coded genetic algorithm (GA), Full factorial design.	[399, 402–404]
Mechanical behaviour	Print orientation, air gap, material temperature, print width, material colour, the thickness of the print layer, raster angle, immersion time in chemical,	Full factorial design, fractional factorial design, Group method of data handling (GMDH), Analysis of variance (ANOVA), Central composite design (CCD), Differential Evolution (DE)	[393, 405–408]
Manufacturing duration	Print orientation, contour width, print width, raster angle, layer thickness.	Coded genetic algorithm (GA), Taguchi's design matrix, Orthogonal array (OA), Analysis of variance (ANOVA), Full factorial design	[403, 409, 410]
Material behaviour	Air gap, raster angle, layer thickness, print width, scan speed	Orthogonal array (OA), Analysis of variance (ANOVA), Signal to noise ratio (S/N), Taguchi method, Main effect analysis, Response surface methodology (RSM).	[411–413]

10.1 Infill pattern, percentage and ratio

Different infill patterns such as linear, grid, triangular, rectangular, hexagonal, diamond, honeycomb, wiggle, etc., can be applied during 3DP [204, 338]. The **Figure 33** shows different infill patterns applicable with additive manufacturing. It influences the print impression [181]. The amount of material in the sanctum of the 3DP part accounts for the infill density and percentage. This is responsible for determining the final strength, weight and hardness of the element [174]. A variety of ranges encompassing print density and patterns are available. They have a substantial impact in the case of attaining maximum optimization regarding print duration and material consumption [173]. A study conducted by Baich et al. [414] shows the analysis and estimation of cost-time relation based on infill pattern. The raster width, angle, slice height, air gap between the raster, etc., are important factors to consider while working with infill pattern and density [414, 415]. They are shown in the **figure 32 (a)**. The rise in infill rate improves both the tensile strength and compression energy of any sample [2]. Rayegani and Onwubolu [408] concluded from their experiment, raster angle of 50^{o}, print width of 0.2034 mm, and air gap of -

0.0025 mm (negative air gap represents overlap) account for the maximum optimized mechanical strength for ABS printed with FDM. In the case of polycarbonate (PC) printed with FDM, the optimum parameters for tensile strength are raster angle 45° and print width 0.6064 mm [416]. An investigation carried out by Lee et al. [403] and Laeng et al. [412] proved in their study that air gap as well as raster angle are critical in determining the elastic performance of ABS printed part with FDM. Akande et al. [417] showed using fused filament fabrication (FFF) technique that fill density has considerable impact on mechanical property of the printed part. The **Figure 32a,b,c** demonstrate three different infill density and percentage for a specific infill pattern. There is a relationship between porosity and mechanical properties in case of FDM fabricated structure [406]. Microstructural and photo micrographic analysis revealed that with decrease of the infill percentage both permeability and porosity of the printed part increases and this can showcase a disproportional relation with mechanical properties as well as hardness of the printed parts [197]. As demonstrated in the **table 13,** the effect of hardness with the change in infill percentage and different infill patterns applicable with 3DP are presented in the **figure 33**.

Table 13: Effect of infill material on the hardness of the 3DP part

Materials	*Increase in composite infill*	*Effect on Hardness*	*Reference*
PLA Matrix + PVC	PVC	Decreases	[197]
PLA Matrix + Wood Powder	Wood powder	Decreases	
PLA Matrix + Fe_3O_4 Powder	Fe_3O_4	Increases	

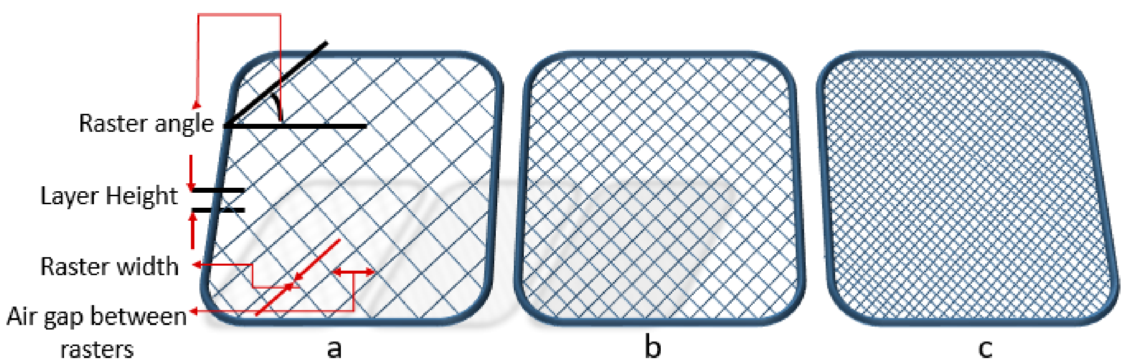


Figure 32. a) *Demonstration of the raster width, angle, layer height, raster to raster air gap, reproduced with permission.* [414] *Copyright © 2015, Inderscience Enterprises Limited (UK).* ***b), c)*** *Different infill percentage of the same infill pattern*

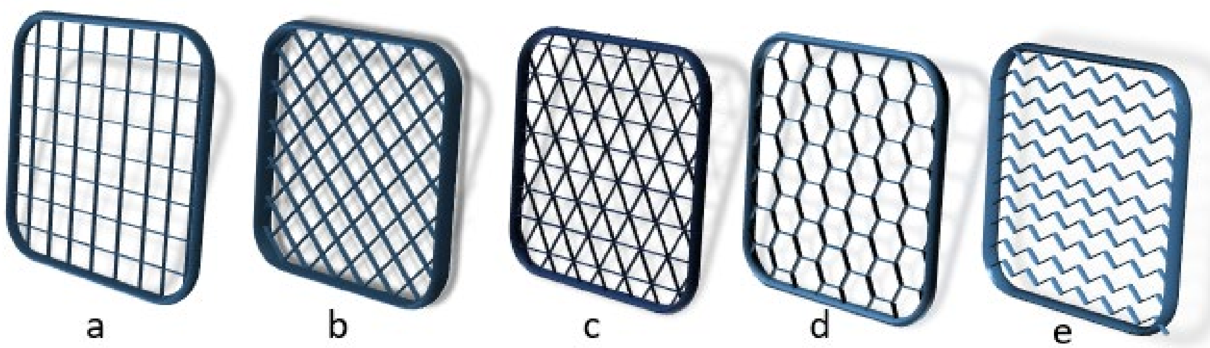


Figure 33. *Different infill pattern applicable with 3DP* ***a)*** *grid,* ***b)*** *rectilinear,* ***c)*** *triangular,* ***d)*** *honeycomb,* ***e)*** *wiggle structure*

10.2 Print orientation

Orientation is the way of material arrangement inside a build platform [391]. The mechanical characteristics, as well as the dimensional integrity of any 3DP object, are directly connected with the quality of orientation. Normally, the deposition direction factors the raster orientation of constituent polymer molecules. The orientation angle further impacts the ductile-brittle nature of the printed element [173]. Letcher [168] investigated 3DP with PLA at different raster angle and found the peak tensile strength at 45°. Grimmelsmann et al. [27] studied the auxetic 3DP structure on a stretchable knit fabric that concluded printing angles other than 45° are also suitable to produce an ideal structure. Ahn et al. [405] found that apart from the air gap the print orientation of the raster has a significant impact on anisotropic behaviour and mechanical strength (especially tensile strength) of printed ABS. Further, Ziemian et al. [230] showed how mechanical properties and structural integrity of FDM printed ABS parts rely on different raster orientations. Four orientation angles, namely longitudinal (raster is aligned with horizontal axis), diagonal (raster at 45° with the horizontal axis), transverse (raster perpendicular with horizontal axis) and crisscross (raster at +/-45° angle with horizontal axis) are shown in the **figure 34**. The impact of print orientation on the mechanical properties of printed part with both ABS and PLA are also highlighted in some other studies [418, 419]. The optimised print orientation to be 0° applying full factorial design, GMDH and DE methods on FDM technique [408]. Lee et al. [411] found that raster orientation also impacts the elastic performance of on FDM printed ABS significantly. The requirement of appropriate print direction is also to make these structures rugged and durable [198]. For instance, Mikkonen et al. [420] facilitated the implication of two important mechanical characteristics. Following the SFS-EN ISO 13934-1, they investigated the impacts of breaking force and elongation to find out the flexibility at various print directions (parallel, plain and orthogonal pattern) of the materials under scrutiny. Additionally, this experiment produced an idea of how the wearable garments made with such materials would behave when prepared with the aforementioned print directions [45].

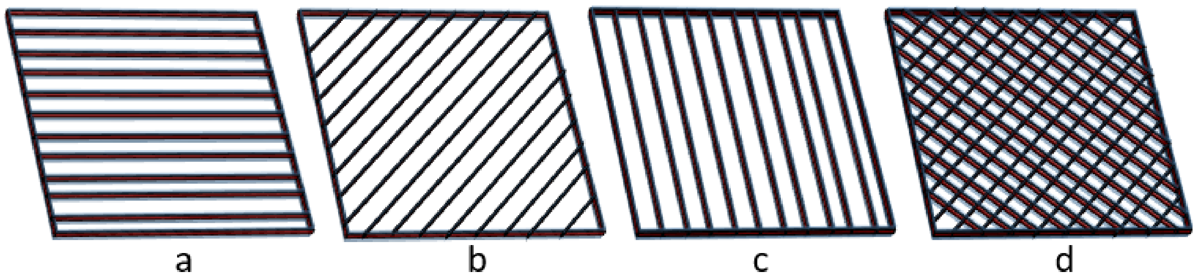


Figure 34. *Different print raster orientation* ***a)*** *longitudinal, 0°,* ***b)*** *diagonal, 45°,* ***c)*** *transverse, 90°,* ***d)*** *crisscross, +45°/-45°, Reproduced under the terms of the [Creative Commons Attribution 3.0 License](https://creativecommons.org/licenses/by/3.0/) (https://creativecommons.org/licenses/by/3.0/).* [230] *Copyright © 2012, IntechOpen.*

10.3 Print layer thickness and print size

The thickness of the print layer has a substantial impact on the mechanical properties of the printed part. [419] demonstrated in their research work on 3DP part with PLA how layer thickness correlates to mechanical behaviours. Similar work was conducted by Rankouhi et al. [418] on 3D parts printed with ABS. Khatwani and Srivastava [421] concluded from their study on additive manufactured PLA that, while flexural strength demonstrates an upward trend with the increase of layer thickness, the tensile strength dives downward. Anitha et al. [402] and Horvath et al. [404] highlighted that in the case of ABS printed with FDM, the layer thickness is rather the most influential factor in reducing the roughness of the surface. A further study conducted by Akande et al. [417] concluded that, print layer thickness has a significant impact on flexural, tensile and impact behaviour in the case of fused filament fabrication (FFF) technique. Lee et al. [411]s and Laeng et al. [412] idetified that the thickness of the print layer has a significant impact on the elastic behaviour and performance displayed by ABS prototypes. An increase in print height results in a degradation of adhesion strength [175]. Kim et al. [147] experienced a decrement in durability and endurance of the print when the height exceeds 200 micro meters. Zhang and Chou [413], in their study, established a positive correlation between layer thickness and residual stress as well as part distortion. On the contrary, increase in layer height reduces the count of the layers which consequently improves printed part resistance [393]. The **Table 14** accounts for typical layer thickness applied during 3DP process

Table 14: Layer thickness with nozzle diameter for different 3D printers

Printer Name	3DP Technology	Print Material	Layer thickness (mm)	Reference
Orcabot XXL	FDM	PLA	0.2	[211]
		PLA and Soft PLA		[238]
Cubicon Single	FDM	NinjaFlex®	0.2	[4]
EOS Formiga P1	SLS	Nylon	0.1	[185]

Below **table 15** shows the maximum print size capacity for different AM technology used in the fashion industry [3]

Table 15: Typical maximum print size capacity utilized by different designers

AM technique	*Print Size (Maximum) mm*	*Brand/Designer*
FDM	490 X 390 X 200	***Iris Van Herpen***
SL	2000	***Iris Van Herpen; Lady gaga***
SLS	80 X 95	***Dr. Richard Hoptroff***

10.4 Speed and Time

One of the downsides of the 3D shaping technologies is that processes like SLA, SLS, FDM, FFF are still slower than the conventional production processes. So, in order to reduce printing time, they are most often combined with other production technologies or printed as a multi-material in combination with other objects like textiles [27, 238]. Zhang and Peng [400] utilised the Taguchi method combined with fuzzy logic in their study to determine optimized values of extrusion and filling speeds 20 mm/s and 30 mm/s, respectively, concerning the dimensional error. Despite being relatively faster, inkjet printing and DLP techniques are limited due to a lack of printable materials [422]. DLP technique is a s little faster than the conventional SLA method [423]. With an increase in printing speed, the adhesion strength both before and after washing decreases [175]. Geng *et al.* [395]explained the outcome of extrusion velocity and printing speed on the printed part dimensions during the FDM extrusion process. Akande et al. [417] concludes that printing speed has a substantial impact on the printed part's mechanical behaviour deposited with the FFF technique. The **Table 16** shows different printing speed of different popular FDM 3D printers with different printing materials of recent times.

Table 16: Speeds of different 3D printers with different print materials (For FDM technique)

3D Printer	3DP Material	Printing Speed (mm/s)	Reference
Cubicon Single Plus FDM printer	TPU and SMTPU	50	[179]
M3036 FDM Desktop Printer	PLA/PEG600/CNF Biocomposite	40	[1]
Ocrabot XXL	Filaflex	50	[7]
Hermes X1 Model	PLA monofilament	40	[161]
MakerBot Replicator 2x	PLA	100	[168]
Cubicon Sinlge	NinjaFlex®	40	[4]
WANHAO Duplicator 4/4x	PLA-Carbon Black (CB) fillers	60	[30]
Cubicon Desktop 3D printer	TPU filament	10	[2]

TPU = Thermoplastic polyurethane, SMTPU = Shape memory thermoplastic polyurethane, PLA = Poly Lactic Acid, PEG = Poly ethylene glycol, CNF = Cellulose nanofibrils

Kim et al. [147] demonstrated a DLP 3DP technology and printer to print polyurethane acrylate polymer at the speed of 6.2 s/100 micrometer. It is possible to get printing speed as much as 216 mms^{-1} incorporating continuous interface liquid production technique along with DLP 3DP method with epoxy thermoset composites [422]. Work by Stampfl et al. [397] on a micro-SLA technique exhibits the writing speed of as much as 500 mms^{-1} with printing material encompassing hybrid sol-gel to cross-linked elastomers. The general speed of 3DP using printers EOS P396 (SLS) and project 1200 (SLA) was found to be 48 mm/h and 14 mm/h, respectively [424].

Time can be considered as the aftermath of speed. Therefore, it has a direct connection to speed. The speedier the processes, the lesser time required. Direct fabrication from a computer-controlled fabricator has proven out to be quite significantly influential in terms of reducing operation duration [230]. Research work conducted by Thrimurthulu et al. [403] suggested that print build time can be significantly optimized by selecting the proper print orientation. They also developed a mathematical model which can predict the optimized condition in this regard. Nancharaiah [409] implemented DOE in FDM to find out optimized production time based on different process parameters. According to this study, layer thickness (66.57%) and air gap (30.77%) influences the printing duration. Further, another study suggested print orientation, as well as layer thickness, are two of the most critical factors influencing print duration [410]. Spahiu et al. [7] developed a complete garment using 3DP that took approximately 75 hours to complete. Multi-nozzle based 3D printers can allow a considerable reduction in time that occurs in the case of single nozzle 3D printers [197]. Since different 3DP techniques are carried out under different conditions, printing duration is bound to vary. It can also differ based on different printing materials used for the same technique. For instance, comparison among such two 3DP techniques with similar parameters to print same 3D shape shows considerable diversity in print duration. The results of research performed by Kim et al. [147] is presented in the **table 17**.

Table 17: Direct comparison of the print duration required to print same 3D shape by FDM and DLP 3DP technique [147]

3D Printer	3DP material	Print duration	Reference
DLP	Polyurethane acrylate photopolymer	9 min 37 s	[147]
FDM	ABS	204 min 31 s	

ABS = Acrylonitrile butadiene styrene

According to study conducted by Nancharaiah [409], 0.33 mm layer thickness, 0.02 mm air gap and 30^{o} raster angle showed the best-optimized result in terms of print duration. Further, in SLS technology, delay time (laser exposure time difference between 2 points on successive scanning) has substantial impact on the mechanical properties of ABS printed part [425].

10.5 Temperature

Costa et al. [426] mentioned the importance of knowing the development of print material temperature and heat transfer process while being fused, deposited and cooled off. Another study describes the importance of temperature profile under different conditions on the mechanical characteristics and integrity of the printed part [427] Mpofu *et al.* [175] stated temperature shows a positive correlation with the tensile strength of the 3DP objects. Viscosity plays a vital role in achieving good strength since lower viscosity accounts for better penetration of 3DP materials. Higher temperature delivers printing paste with lower viscosity and thus contributes to higher adhesion force. It is necessary for the printed materials to carry high temperature to ensure effective bonding and generate enough adhesion [426]. Higher material temperature is also responsible for the reduced roughness of the print surface [404]. Geng *et al.* [395] further suggested, temperature affects print polymer rheology, and it is important to achieve a desired 3DP part deposited by the FDM technique. Research conducted by Khatwani and Srivastava [421] established a positive correlation between print bed temperature, and tensile-flexural strength of PLA printed parts deposited by additive manufacturing. Examples of typical nozzle and print bed temperature required by different materials in the case of FDM is shown in the **table 18** below.

Table 18: Nozzle and print bed temperature of different FDM 3D printers with different print materials for FDM technique

Print Materials / Composites	Nozzle Temperature (°C)	Bed Temperature (°C)	Reference
TPU	230	0	[179]
SMTPU	230	50	[179]
PLA-Keratin composite	190	Room temperature	[176]
Nylon white (Nylon 6)	275	Not heated	[153]
PLA/PEG600/CNF Bio composite	210	Not heated	[1]
PLA Monofilament	215	60	[161]
Filaflex	245	65	[7]
Filaflex	245	Not heated	[199]
PLA	190-210	Room temperature-80	[211]
PLA	230	65	[168]
NinjaFlex®	230	40	[4]
PLA and Soft PLA	200	60	[238]
TPU filament	230	50	[2]
ABS	240	Not heated	[199]

TPU = Thermoplastic polyurethane, SMTPU = Shape memory thermoplastic polyurethane, PLA = Poly Lactic Acid, PEG = Poly ethylene glycol, CNF = Cellulose Nano fibrils

10.6 Cost

3DP is becoming affordable gradually [168]. Kumar *et al.* [197] stated 3DP with polymer material is a low-cost operation. Among different processes, FDM is seeking attention as it accounts for low primary set up cost along with simple operating procedure compared to SLA, SLS, etc. [27, 68]. FDM process parameters are also important factors in the case of defining the cost [391, 395]. Kim et al. [147] highlighted about the towering cost of SLS equipment, and so performed research on DLP 3DP technology. Therefore, this extrusion process is typically incorporated as the basis for the most accessible and lowest cost 3DP technology [167]. The lower production economy of entry based extrusion-based printers can therefore be credited to the additive manufacturing technique [414]. On the other hand, the longer time required to produce a large textile structure can make the process economically unprofitable at times. So it has proved to be more economical to use this technique as a subsidiary and add on the process to stick small 3DP parts with conventional fabric [174]. In the case of additive manufacturing by extrusion, the comparison of price between printing material and device cost proves the latter to be significantly lower [428]. Printing on demand objects helps to reduce inventory cost significantly [3]. Apart from the printing process being quite economical, Faruk et al. [429] and Flores-Hernandez et al. [176] believe that it is possible to reduce cost substantially by using natural fillers with polymer matrix as printing paste. Usage of multifunctional materials performing multiple functions as printing paste ensures the agility and autonomy of the process.

10.7 Adhesion

For the application of mass customisation of textile products, 3DP on textiles is creating possibilities over time [430]. Composites made by 3DP of polymers on textile fabrics are being used for making specific featured textile products where maintaining adhesion between both materials (printing polymer and textile substrate) has become a demanding task [199]. Optimisation of the adhesion behaviour between the 3DP polymer material composite and the base textile substrate can help the multilateral composite to be designated as the 3DP material. Although this has increased possibilities for new textiles applications, there have been challenges in the adherence of the 3D printed polymer to the textile substrate [240]. Some papers have discussed the investigation for adhesion improvement [45, 174, 431] and their testing processes [430]. Different techniques were invested in improving adhesion are summarised in the **table 21**. For instance, more efficient adhesion can be achieved by modifying the surface through a mechanical and chemical process. Polymer coating on different textile fabric has a great influence on adhesion [45]. NaOH (Sodium hydroxide) also helps to improve adhesion between the PLA (Poly-lactic acid) matrix and reinforcement [176]. Kozior *et al.* [236] experimented on associated distinct pretreatments of a cotton woven fabric for 3DP with poly-lactic acid (PLA), along with several infill orientations of the first printed layer to identify their influence on adhesion property.

10.7.1 Factors influencing adhesion

Several factors (shown in the **figure 35**) like printing area ratios, pre-stretch, and fabric properties (fabric configuration, fabric concentration, and opening geometry) have a great influence on adhesion between printed polymers and the textile of hybrid three-dimensional 3DP textiles [198, 233]. The practical importance of infill angle, which is a 3DP parameter, came into light from the study of Kozior *et al.* [236] that shows a strong correlation of adhesion force with infill orientation. It has been shown that the adhesion forces go up from 0° to 90° and declines for even greater infill angles. 90° infill orientation can be considered for high adhesion force. According to Tello et al. [432], a balance between contact area and gap is necessary for maintaining adhesion. Better adhesion can be obtained by the larger contact area between print and textiles.

Moreover, various 3DP parameters like speed, print platform temperature, etc., can impart a noteworthy consequence on the adhesion behaviour of polymer print materials to fabrics. But a substantial influence on adhesion strength cannot be produced by platform temperature if the glass transition temperature of the applied fabric like nylon is higher than this temperature [220]. There seem to be apparent seam lines among layers in 3DP following temperature fluctuations that can impact the strength of the bond between layers [43, 433]. Also, because the temperature fluctuates during processing within the printer, the bond strength between layers can be affected [3, 5].

A relation exists between print speed and the thickness of the layer, which affects the adhesion property of 3DP. The highest 3DP speed causes lower layer thickness, and the highest adhesion force can be obtained by maintaining printing speed in the middle ranges [220]. Because of printing first, the boundary of the printed section shows a higher level of adhesion, and afterwards, the centre possesses a minor level of adhesion [198].

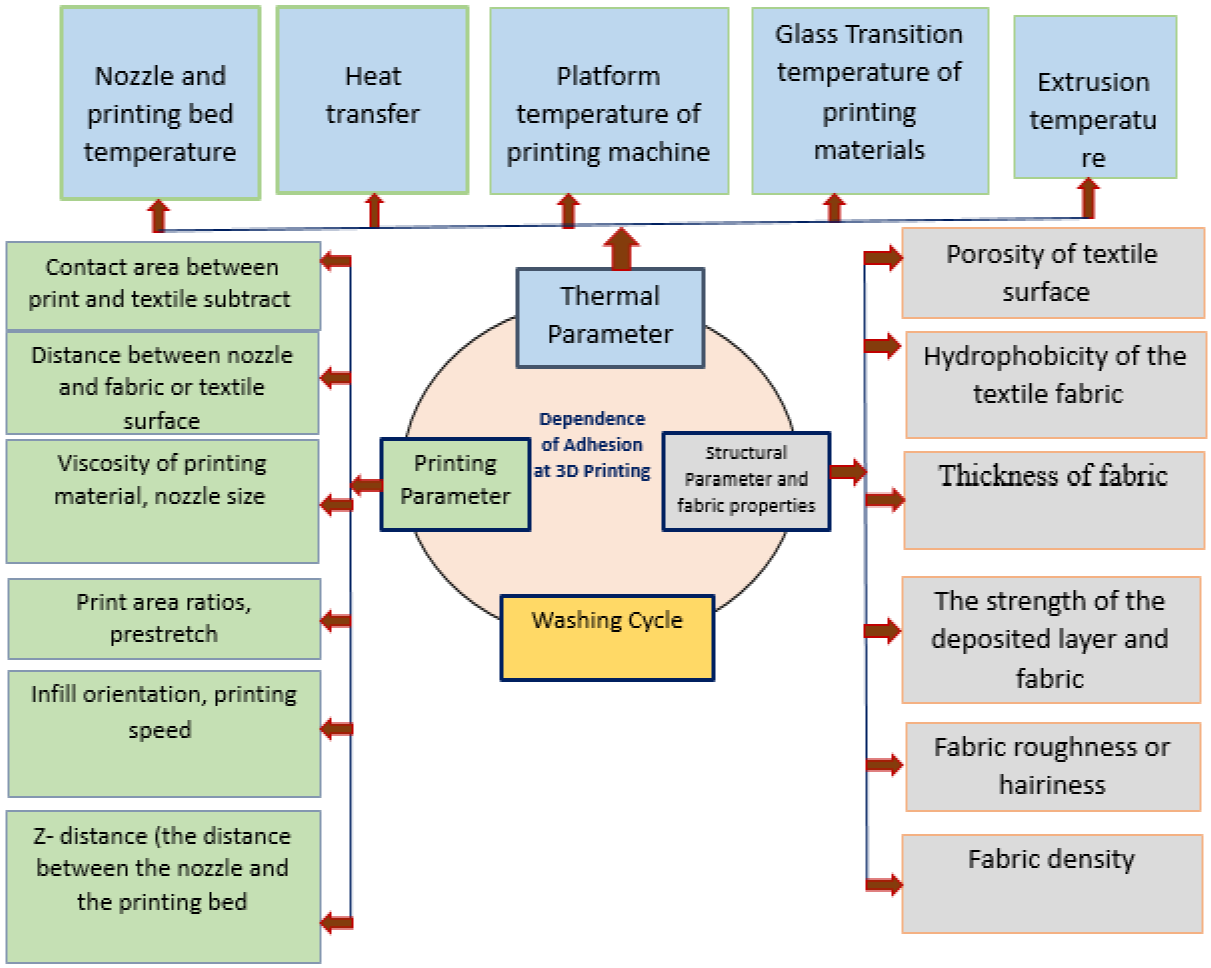


Figure 35. *Several factors that affect adhesion at 3DP Textiles Process*

10.7.2 Adhesion of 3DP filaments

An investigation directed by Pei et al. [45] to detect the adhesion of polymer materials used as 3DP filaments that are directly printed onto fabrics found that the woven poly-wool, cotton woven, and soy knit fabrics execute the foremost adhesion with three types of polymers such as acrylonitrile butadiene Styrene (ABS), poly-lactic acid (PLA) and nylon filament. Owing to the free-standing fibres or roughened and hairy surface of a fabric, the great adhesion between the polymer parts and cotton, soy and poly-wool fabrics could be allowed [68, 236] but in case of other fabrics, partaking smoother surface finish did not permit decent surface adhesion [45]. When PLA and PLA nanocomposites are deposited on PLA fabrics, a higher adhesion force can be obtained [220]. It had also found that PLA has better adhesion as compared to other printing filaments such as ABS and Nylon [45, 233, 364, 432].Polyester based thermoplastic polyurethane

(TPU) shows better adhesion behavior than thermoplastic styrene (TPS) compounds when they were applied on woven or knitted textiles substrates made of polyester (PES), cotton, or aramid (AR) but polyester based TPU prone to partial degradation in presence of moisture [174]. A polyester fabric that has high thickness shows high adhesion property [233]. Korger *et al.* [174] also estimated the compatibility by adhesion of different flexible thermoplastic elastomers printed on numerous woven and knitted work-wear and sportswear fabrics, mainly prepared from cotton, polyester, or aramid like textile substrates. The regression model, which was deliberated by Mpofu *et al.* [175] showed that during printing Poly-lactic acid on cotton fabric, a significant impact of extrusion temperature, speed, model height remains on adhesion force.

10.7.3 Adhesion quality

Adhesion quality defines the degree of attraction between two dissimilar phases, such as cohesion between textiles and 3DP materials, during the production of 3D printed composites. During making 3DP composites structure, good adhesion quality is required to maintain. So, adhesion testing is done to identify the adhesion quality of bonding created between 3DP polymers and textile substances to find out the force required to cause fraction. Perpendicular tensile test, the peel test, and shear tests were conducted to identify the adhesion of a 3DP profile on textile substrates [430]. Through these types of tests, qualitative measurement of adhesion is done. Through peel strength test on polyester jersey weft-knitted fabric using polylactic acid (PLA) as printing material to identify the adhesion between printing materials and textile substrate, it was found that increasing fabric width ratio is a reason for higher peel strength or higher adhesion, but a reduction of the peel strength or adhesion happens if the width of the printing polymer increases [198]. Applying quartz crystal microbalance with dissipation monitoring (QCM-D), peeling and washability tests, it was observed that cellulose acetate (CA) shows better affinity and adhesion properties than acetoxypropyl cellulose (APC) because the lines construction of CA enriches the material's ability to get aligned well with existing cellulose molecules found in the substrate. It is accountable not only for decent adsorption but also improved adhesion characters for the printed configurations [28].

Adhesion is an important factor as it affects the end uses, durability and quality of the product. There are different mechanisms for the polymer to substrate adhesion, that is, molecular bonding, mechanical interlocking and thermodynamic adhesion [434]. By setting control parameters correctly, printing polymers to textiles adhesion is possible to develop to a great extent [198].To point out adhesion behaviors and process controlling parameters which produce the best result, dedicated research is essential to perform [220]. A summary of different methods to improve 3DP adhesion is presented in the **table 19.**

Table 19: Methods related to the improvement of adhesion for 3DP

Methods	Materials	Testing	Printing Method	Reference
Increasing adhesion strength by the polymer coating	1.Cotton woven fabric 2.Poly-lactic Acid (PLA) (5% dissolved in hot 1,2-dichlorobenzene) 3.Acrylonitrile Butadiene Styrene(ABS) (5% dissolved in acetone) 4. Poly-methyl methacrylate(PMMA), 5% dissolved in acetone) 5.Polyamide(PA) (Soluble amorphous co-polyamide from Îµ-caprolactam, hexane-1,6-diamine, hexanedioic acid and 4,4-diaminodicyclohexylmethane, 5% dissolved in 80% ethanol and 20% water).	Performing adhesion test was carried out by using a universal testing machine. This is following DIN 53530, assessed following the ISO 6133 and applying the method for more than 20 peaks.	3DP was performed via Fused Deposition Modeling (FDM) 3DP technology using Orcabot XXL 3D printer with 0.4 mm nozzle diameter, 0.2 mm layer thickness, 200 °C nozzle temperature for PLA and 220 °C for (ABS) and 60 °C printing bed temperature.	[237]
Improved adhesion by textile surface treatment (e.g. washing, roughening, finishing, and plasma) to treat the textile product surface characteristics like wettability or hairiness.	1.Flexible materials for printing: For example, Soft PLA and a thermoplastic elastomer (TPE), 2.Enzyme amylase and the washing agent Kieralon CD (BASF), 3. Polyester, cotton and wool, argon (Ar) and nitrogen (N2), carbon dioxide (CO_2) for plasma treatment.	Accomplishment of adhesion test by separating layers of laminated woven fabrics according to DIN 53530, using a testing device called Zwick Roell.	Fused Deposition Modeling (FDM) 3DP technology was applied with the FDM printer X400 manufactured by German RepRap GmbH.	[68]
Using NaOH (Sodium hydroxide) to improve adhesion between PLA	1.Polylactic Acid (PLA) filament (natural colour, 3mm), 2.Keratin bio-fibre (reinforcing natural material), 3.Sodium Hydroxide	The storage modulus (E') and the tan delta (Tan δ) were used as a temperature function of the composites were	The 3DP composites were manufactured using an extrusion-based 3D printer	[176]

matrix and reinforcement		evaluated by DMA(Dynamical mechanical analysis)	(Industria 55, Queretaro, Mexico).	
Form-locking connections to improve adhesion forces	1.PLA (Poly-lactic acid) 2.The knitted fabrics which made by Polyester (PES), Polyamide / Nylon (PA/Nylon), Polyacrylonitrile (PAN)	According to DIN 53530 standard, adhesion tests were executed and appraised according to ISO 6133 by using 20 peaks for obtaining adhesion related results.	FDM printer named Orcabot XXL manufactured by Prodim (The Netherlands) was used for 3DP.	[210]
By maintaining 90Â° infill orientation for increasing adhesion force	1. Cotton woven Fabric 2. Glue stick 3. Hairspray 4. Acetone (1 h, afterwards washing in water) 5. NaOH (30 s in 0.2M NaOH, afterwards washing in water) 6. 400 grit size abrasive paper 7. PLA, ABS or nylon	Adhesion was measured according to 53530 & results were evaluated according to ISO 6133 using more than 20 peaks.	Printing PLA polymer using FDM printer named Orcabot XXL on cotton woven fabric.	[236]
Decreasing Z-distance (the distance between the nozzle and the printing bed) for increasing adhesion	1.PLA 2.Different cotton woven fabrics	According to DIN 53530, adhesion tests were executed & ISO 6133 was used to evaluating the result	3DP was done by using an FDM printer named Orcabot XXL with PLA printing material on different cotton woven fabrics by varying thickness	[242]
Increasing yarn density, i.e. the number of warp threads per centimetre for high adhesion	1.Polyamide 66 (PA66) and polylactic acid (PLA) fabric, 2.PLA, PLA nano-composites, nylon 3.Nanosize carbon black/PLA (CB/PLA) and multi-wall carbon nanotubes/PLA (CNT/PLA) nanocomposites	Using a standard test method following SS-EN ISO 11339:2010, using a Zwick/Z010 tensile tester, adhesion tests were performed with a 100 mm/min separation rate.	Deposition of polylactic acid (PLA) on Polyamide (PA) was done by FDM technique.	[220]

10.8 Drape/Flexibility

Textile structures printed with 3D printers have the potential to exercise mechanical properties of the materials along with achieving inherent flexibility and stretchability of textiles [185]. Work by Crookston et al. [435] states how an assembly of disconnected equivalent interlinks can impart non-linear force-displacement and nonlinear spring behaviour in the form of a rapidly manufactured textile structure. Such structures are capable of showing a higher degree of out-of-plane and sheer flexibility. Hopkinson [436] mentioned of a dress printed with SLS incorporating multiple assembly of separated items that ensures flexible adaptation of any design. Different works introducing flexibility to 3DP textile structures have taken place based on chainlike structure, closed-loop geometry, interlinked closed geometry, continuous fibre geometry, etc. [185]. Bingham *et al.* [50] highlighted the process of fabricating a 3D textile structure using a rapid manufacturing technique that shows drape and flexibility like conventional textiles. 3DP textile woven fabric structure using ABS print material and the FDM technique is found to demonstrate a flexible, textile-like behavior [204]. Fabrication of a weft-knitted single-faced structure, lace pattern, and multi-materials model using soft PLA shows closer flexibility towards conventional textile counterparts when printed with FDM technique rather than with SLS [167].

11. Benefits and drawbacks

3DP technology and the associated application areas are growing fast in the fashion industries, delivering superior outputs in many respects compared to other processes that are being used for similar operations [265]. But the technology also has its shortcomings.

11.1 Benefits

3DP techniques provide significant improvement in manufacturing prototypes and small samples but also is capable of creating complex models with vast design variation [167, 186]. It is pretty handy to work with the 3DP process to create complex structures even as fine as 0.01 mm (using SLA) [172]. In fact, 3DP can be differentiated from casting and machining like traditional fabrication processes because of this capability to produce complicated configurations with minimum possible waste [202]. While the printing speed is considered slower than traditional textile manufacturing, radical reduction of the textile process chain length is responsible for compensating the problem of the current low speed of the commercial 3D printers. For example, in the case of 3DP garment, some processes are eliminated, such as fibre preparation, spinning, weaving, dyeing, finishing, cutting and sewing. There are also reductions in transportation needs and the time between an idea and a product. Also, energy costs are kept in the minimum possible part [204]. Adding to that, for the ease of product modification, the reverse engineering method can be used with 3DP. An essential reduction of some of the constraints often encountered with the traditional subtractive processes, such as costly machinery, complex workflow, high labour inputs, and the enormous resource and material waste, can be the most attractive ability of this transformative technology [437].

Kim *et al.* [147] declared FDM to be the most used 3DP technique due to its low installation cost, whereas other 3DP technique like SLS can provide accurate product with proper strength. So liberty with design, rapid iteration [438], fabricating rigid material based flexible objects [365], fairly efficient customisation of the part to be printed, and minimum waste generation [7] contribute largely to its advantage [1]. According to a study conducted by Ahrendt et al. [29], the fusion of 3D scanning along with computer-aided engineering (CAE) modelling and actual printing can unleash wonderful possibilities in the area of custom made products. Control over deposition of material eases the custom made fabrication of any product [31]. Adding to that, the flexibility to utilise and select from a wide range of biological, synthetic, multifunctional materials [180], photopolymers [147] and polymer matrix composites (PMC) [438] available makes the process more versatile [1, 9]. In SLS, any powder formed raw materials such as metals, polymers, ceramics, composites, etc., is usable [130]. As mentioned by Singh, Ramakrishna and Berto [438], with LOM, it is possible to include even paper, films, foils, metal laminates, etc., to fabricate 3D prototypes. Multi-material printing and dual extrusion can be carried out via printers installed with a multi-nozzle based system at the same time [197]. Moreover, some 3DP object on textile substrate exhibit potentially good adhesion and decent fastness to washing because of polar interaction in the case of thermoplastic print materials [174]. From the end product's perspective, 3DP objects on textile substrates can attain sufficient flexibility [439] as well as position-dependent mechanical properties [231]. Research work conducted by Eutionnat-Diffo *et al.* [243] demonstrates better dimensional stability and stiffness of 3DP part on polyester fabric. Prominently, directly printed 3D textile structure show fair resistance and provide decent reinforcement as well [161]. Kozior et al. (2019) [211] performed research on how AM can contribute to improving the mechanical durability of electrospun nanofibre mats. [197] highlighted printing parts could contain embedded sensors compiled of conductive and piezo responsive materials which are capable of producing digital readings. Studies conducted by ten Bhömer *et al.* [439] showed, more efficient results can be achieved from 3DP on textiles by controlling unwanted variations, control factors and noise factors utilizing robust design methodology (RDM). The elimination of steps required for traditional textile manufacturing, inventory, warehousing, packaging, transportation, etc., keeps the 3DP process quite economical [3, 7]. The high probability of cost minimisation as well as the far-flung latitude of the technology has the ability to allow designers to fabricate parts with novel characteristics. Those can be integrated into different functional applications [265]. Regarding the size of printers, Yap and Yeong [186] highlighted, smaller desktop 3D printers are quite inexpensive & economical while larger industrial scale printers can produce a larger variety of objects. Comparing to the traditional processes, 3DP can additionally offer advantages by providing practical solutions and technical support concerning great labour intensity, high safety threats and extended building phases of traditional construction methods [67, 440]. On top of that, 3DP technology has become very familiar for its sustainable issue like zero-waste production capability [18].

11.2 Drawbacks

All surface structures such as the double face, zigzag, etc. are not considered much suitable for 3DP [352]. Printing irregularity, as well as notch wear on wavy surfaces, are seen as factors contributing to the failure of printed samples when elongated at different order [216]. Furthermore, printing speed being slower than conventional textile production machines (such as weaving, knitting, etc.), incompatibility of raw material with printer [197], etc., are considered significant drawbacks. Difficulties regarding viscosity [7], insufficient flexibility, comfort, strength as well as lack of softness, elasticity, moisture and heat control ability compared with the traditional textiles pose quite a challenge [174, 175]. Korger *et al.* [174] also stated deposition of flexible filaments by FDM is quite troublesome. Kozior et al. [211] mentioned a problem regarding detachment of electrospun nanofibre mat from printing bed after printing is done with additive manufacturing. Another disadvantage with 3D printers might be presented as their limited capacity to process a large volume at a time and might be required to break or segment the printing part into several fractions [29, 186]. Generation of large anisotropies propagated by inconstant porosity [30] or voids [441] and longer print duration [231] are amongst some of the other disadvantages worth mentioning. The fact that information on static raw materials received from the database is not always reliable makes the material selection process difficult [32]. Typically, raw materials are limited to solid form for FDM 3D printers, while powder or liquid raw materials are fed to SLS or SLA printers [7]. Also, when separate parts are produced, Spahiu et al. [7] highlighted it is difficult to join those into one as the contact area is relatively smaller. Despite having the aforementioned drawbacks, 3DP is still a very potential proposition for the future.

12. Summary and conclusion

3DP techniques will play key role in 4th industrial revolution. Future of 3DP will bestow us with less expensive but more customised products and higher co-design options for the customers [442]. However, despite the fact that 3DP has already been proven to be a wonderful complement to fashion designers, there is still much work to be done and many issues to be resolved such as fine finish, durability, duration of the print and the manufacturing costs [304, 443, 444]. On top of that, substantial material consumption, significant changes in the workforce pattern as well as higher facility set up investments, etc., are some crucial factors that are needed to be addressed [445, 446]. In terms of generally used materials, although a wide variety of polymers, ceramics, metals and composites are available for 3DP, there is still a lack of suitable print elements with proper mechanical properties, multi-functionality, electrical, thermal conductivity and endurances [447].

There are huge potentials of making customised textile, apparel, fashion accessories by 3DP. However, some improvements are yet to be carried out on the existing 3DP techniques to fabricate textile-based products suitable for human wearable applications. To produce daily wearable clothing, which will provide flexibility and comfort, some areas of existing 3DP technologies as well as materials need further improvement [186] [250]. Considering this, the latest 3DP machines and materials are being developed, keeping an eye on the detailed quality of final products [448]. Some of the challenges that the current 3DP throws towards us have been mentioned in section 11.2. Among them, one important example is the construction of complete garments with 3DP involves a great deal of time to print. The materials used for 3D printing of full garment configuration are not capable of offering similar flexibility and drapability like the traditional textiles. Mostly used synthetic filaments nowadays for making 3DP textiles are not flexible enough and cannot provide the necessary ease [26, 86, 186].

Sustainability has become a buzzword of the present time. 3DP technology is very strongly related with sustainable development. The reduced amount of energy use, limited demand for resources and associated lesser CO_2 emissions certainly help to decrease environmental burden. This is also contributing to shift the existing traditional physical product chain towards a more localised, digital value chain [88]. Works have been done on 3DP of fashion garments using recycled polyester filament [200]. It is now possible to make sustainable textile commodities from wood-derived materials via 3DP [190]. Development of carbon fibre-polymer composites via 3DP technique, are dragging attention because of great mechanical strength and durability [202, 449]. In the case of 3DP on textiles or 3D multi-material composites printing, optimisation of adhesion between printing polymers and textile materials plays an important role in 3DP textiles [233]. It is possible to increase adhesion between 3DP polymers and textile substrates by pretreating textiles [231, 236], applying different polymer coatings [237, 238], maintaining printing parameters such as nozzle height, infill orientation [220, 231, 236]. or any combination of these during printing. To gain a better adhesion with the textile fibres, investigating the process of deposition in terms of pressure, temperature, build density as well as the modification of the fibre surface through mechanical or chemical means can also be included [443]. Another challenge comes in the form of washing. Washing is an integral part of textile substrate both in the manufacturing as well as consumer use phase. When it comes to washing, there are still some problems associated with reducing the adhesion of printed textiles [175]. Another important point towards gaining sustainability is whether a product supply chain is too much transport intensive. Since the 3DP supply chain is expected to be shorter than the existing one, it should be less transport dependent [450]. Additionally, Petrovic et al. [87] reports that 40% raw material based waste and up to 95-98% materials reuse is possible with 3DP technology. Adding to that, textile industry is the third highest water consumer sector of the world [258]. Establishment of 3DP in this sector can bring a permanent solution freshwater depletion problem as well.

FDM is a very popular 3DP technique that offers many different printers at a range of very low prices [350]. However, the cost to the environmental balance is not that low. 3DP manufacturing process is highly plastic oriented. Most of the raw materials are various types of plastics all of which may not be recyclable, for example, ABS, polycarbonate, etc. used in FDM [451]. Photopolymers used in SLA can contain toxic heavy metals like antimony [452]. Integration of plastic singularly or in the form of composite with organic materials may contribute handsomely towards global plastic pollution. During FDM printing plastics need to be heated at least one degree higher than their usual melting point [3]. Heating plastics may release fumes or fine particle matters (PM) which are toxic in most cases [453].

Time-saving and cost-saving technologies are demands of today's world to ensure sustainable development. One of such technologies is the 3DP. This review has clearly outlined how the integration of 3DP technology has the ability to revolutionise the textile world. The key challenge of using 3DP to produce textile products is to maintain the characteristics at least similar to conventional textiles, if not any better. This review has presented the principles, developments and technologies of different 3DP techniques. An observation of variant factors and process parameters of the techniques suggest how they can control the behaviour of end products under different circumstances. An overview of printing materials is also presented to show the range of materials that is applicable to 3DP design features on existing basic textile substrates, as well as to print the forms and shapes of textile structures directly. The 3DP on textiles accounts for how combining printing elements with conventional textiles enhances the product novelty and functionality. Attachment of smart electronics by 3DP process includes some very interesting and impressive research works in the field of smart textiles and wearable electronics. Despite having all countless benefits, evidently, 3DP for textiles also has some notable limitations comparing with conventional textile matters. Especially with achieving the complete textile structure, 3DP with textiles still falls short. This has been pointed out very clearly in this review. There are different test methods with respective standards to assess performance, quality and durability of 3DP related to textiles, which are also listed in this review. A promising future roadmap towards the sustainability of 3DP technology in the context of the textile and fashion industry is presented. We believe this review paper has brought together every aspect of 3DP for the textile and fashion industry as a single document, including the understanding of textile structures. This will equip researchers with the facts and figures to discover even more than what is already available in front of us.

Reference

[1] Wang, Q.; Ji, C.; Sun, L.; Sun, J.; Liu, J. Cellulose Nanofibrils Filled Poly(Lactic Acid) Biocomposite Filament for FDM 3D Printing. *Molecules*, **2020**, *25* (10), 2319. https://doi.org/10.3390/molecules25102319.

[2] Lee, H.; Eom, R. I.; Lee, Y. Evaluation of the Mechanical Properties of Porous Thermoplastic Polyurethane Obtained by 3D Printing for Protective Gear. *Adv. Mater. Sci. Eng.*, **2019**, 5838361. https://doi.org/10.1155/2019/5838361.

[3] Vanderploeg, A.; Lee, S. E.; Mamp, M. The Application of 3D Printing Technology in the Fashion Industry. *Int. J. Fash. Des. Technol. Educ.*, **2017**, *10* (2), 170–179. https://doi.org/10.1080/17543266.2016.1223355.

[4] Park, J. H.; Lee, J. R. Developing Fall-Impact Protection Pad with 3D Mesh Curved Surface Structure Using 3D Printing Technology. *Polymers (Basel).*, **2019**, *11* (11). https://doi.org/10.3390/polym11111800.

[5] Huang, S. H.; Liu, P.; Mokasdar, A.; Hou, L. Additive Manufacturing and Its Societal Impact: A Literature Review. *Int. J. Adv. Manuf. Technol.*, **2013**, *67* (5–8), 1191–1203. https://doi.org/10.1007/s00170-012-4558-5.

[6] Lonjon, C. Discover the history of 3D printer https://www.sculpteo.com/blog/2017/03/01/whos-behind-the-three-main-3d-printing-technologies/ (accessed Apr 10, 2021).

[7] Spahiu, T.; Canaj, E.; Shehi, E. 3D Printing for Clothing Production. *J. Eng. Fiber. Fabr.*, **2020**, *15*. https://doi.org/10.1177/1558925020948216.

[8] Sun, L.; Zhao, L. Envisioning the Era of 3D Printing: A Conceptual Model for the Fashion Industry. *Fash. Text.*, **2017**, *4* (1). https://doi.org/10.1186/s40691-017-0110-4.

[9] Wang, X.; Jiang, M.; Zhou, Z.; Gou, J.; Hui, D. 3D Printing of Polymer Matrix Composites: A Review and Prospective. *Compos. Part B Eng.*, **2017**, *110*, 442–458. https://doi.org/10.1016/j.compositesb.2016.11.034.

[10] Gregurić, L. History of 3D Printing: When Was 3D Printing Invented? | All3DP https://all3dp.com/2/history-of-3d-printing-when-was-3d-printing-invented/ (accessed Nov 7, 2020).

[11] Levy, G. N.; Schindel, R.; Kruth, J. P. Rapid Manufacturing and Rapid Tooling with Layer Manufacturing (LM) Technologies, State of the Art and Future Perspectives. *CIRP Ann. - Manuf. Technol.*, **2003**, *52* (2), 589–609. https://doi.org/10.1016/S0007-8506(07)60206-6.

[12] Mudge, R. P.; Wald, N. R. Laser Engineered Net Shaping Advances Additive Manufacturing and Repair. *Weld. J. (Miami, Fla)*, **2007**, *86* (1), 44–48.

[13] The History of Printing - 1ink.com https://www.1ink.com/blog/the-history-of-printing/ (accessed Mar 8, 2021).

[14] Joshi, S. C.; Sheikh, A. A. 3D Printing in Aerospace and Its Long-Term Sustainability. *Virtual Phys. Prototyp.*, **2015**, *10* (4), 175–185. https://doi.org/10.1080/17452759.2015.1111519.

[15] Uriondo, A.; Esperon-Miguez, M.; Perinpanayagam, S. The Present and Future of Additive

Manufacturing in the Aerospace Sector: A Review of Important Aspects. *Proc. Inst. Mech. Eng. Part G J. Aerosp. Eng.*, **2015**, *229* (11), 2132–2147. https://doi.org/10.1177/0954410014568797.

[16] Ganesh Sarvankar, S.; Yewale, S. N. Additive Manufacturing in Automobile Industry. *Int. J. Res. Aeronaut. echanical Eng.*, **2019**, *7* (4), 1–10.

[17] Nachal, N.; Moses, J. A.; Karthik, P.; Anandharamakrishnan, C. Applications of 3D Printing in Food Processing. *Food Eng. Rev.*, **2019**, *11* (3), 123–141. https://doi.org/10.1007/s12393-019-09199-8.

[18] Pasricha, A.; Greeninger, R. Exploration of 3D Printing to Create Zero-Waste Sustainable Fashion Notions and Jewelry. *Fash. Text.*, **2018**, *5* (1). https://doi.org/10.1186/s40691-018-0152-2.

[19] Yan, Q.; Dong, H.; Su, J.; Han, J.; Song, B.; Wei, Q.; Shi, Y. A Review of 3D Printing Technology for Medical Applications. *Engineering*, **2018**, *4* (5), 729–742. https://doi.org/10.1016/j.eng.2018.07.021.

[20] Lee Ventola, C. Medical Applications for 3D Printing: Current and Projected Uses. *P T*, **2014**, *39* (10), 704–711.

[21] Sakin, M.; Kiroglu, Y. C. 3D Printing of Buildings: Construction of the Sustainable Houses of the Future by BIM. *Energy Procedia*, **2017**, *134*, 702–711. https://doi.org/10.1016/j.egypro.2017.09.562.

[22] Toeters, M.; ten Bhömer, M.; Bottenberg, E.; Tomico, O.; Brinks, G. Research through Design: A Way to Drive Innovative Solutions in the Field of Smart Textiles. *Adv. Sci. Technol.*, **2012**, *80*, 112–117. https://doi.org/10.4028/www.scientific.net/ast.80.112.

[23] Lee, J.; Kim, H. C.; Choi, J. W.; Lee, I. H. A Review on 3D Printed Smart Devices for 4D Printing. *Int. J. Precis. Eng. Manuf. - Green Technol.*, **2017**, *4* (3), 373–383. https://doi.org/10.1007/s40684-017-0042-x.

[24] Foo, C. Y.; Lim, H. N.; Mahdi, M. A.; Wahid, M. H.; Huang, N. M. Three-Dimensional Printed Electrode and Its Novel Applications in Electronic Devices. *Sci. Rep.*, **2018**, *8* (1), 1–11. https://doi.org/10.1038/s41598-018-25861-3.

[25] Shahrubudin, N.; Lee, T. C.; Ramlan, R. An Overview on 3D Printing Technology: Technological, Materials, and Applications. *Procedia Manuf.*, **2019**, *35*, 1286–1296. https://doi.org/10.1016/j.promfg.2019.06.089.

[26] Beecroft, M. 3D Printing of Weft Knitted Textile Based Structures by Selective Laser Sintering of Nylon Powder. *IOP Conf. Ser. Mater. Sci. Eng.*, **2016**, *137* (1), 0–7. https://doi.org/10.1088/1757-899X/137/1/012017.

[27] Grimmelsmann, N.; Meissner, H.; Ehrmann, A. 3D Printed Auxetic Forms on Knitted Fabrics for Adjustable Permeability and Mechanical Properties. *IOP Conf. Ser. Mater. Sci. Eng.*, **2016**, *137* (1). https://doi.org/10.1088/1757-899X/137/1/012011.

[28] Tenhunen, T.; Moslemian, O.; Kammiovirta, K.; Kääriäinen, P.; Österberg, M.; Tammelin, T.; Orelma, H. Surface Tailoring and Design-Driven Prototyping of Fabrics with 3D-Printing: An All-Cellulose Approach. *Mater. Des.*, **2018**, *140*, 409–419. https://doi.org/10.1016/j.matdes.2017.12.012.

[29] Ahrendt, D.; Romero Karam, A. Development of a Computer-Aided Engineering–Supported

Process for the Manufacturing of Customized Orthopaedic Devices by Three-Dimensional Printing onto Textile Surfaces. *J. Eng. Fiber. Fabr.*, **2020**, *15* (6). https://doi.org/10.1177/1558925020917627.

[30] Eutionnat-Diffo, P. A.; Chen, Y.; Guan, J.; Cayla, A.; Campagne, C.; Zeng, X.; Nierstrasz, V. Stress, Strain and Deformation of Poly-Lactic Acid Filament Deposited onto Polyethylene Terephthalate Woven Fabric through 3D Printing Process. *Sci. Rep.*, **2019**, *9* (1), 14333. https://doi.org/10.1038/s41598-019-50832-7.

[31] Rivera, M. L.; Hudson, S. E. Desktop Electrospinning a Single Extruder 3D Printer for Producing Rigid Plastic and Electrospun Textiles. *Conf. Hum. Factors Comput. Syst. - Proc.*, **2019**, 1–12. https://doi.org/10.1145/3290605.3300434.

[32] Mueller, J.; Shea, K.; Daraio, C. Mechanical Properties of Parts Fabricated with Inkjet 3D Printing through Efficient Experimental Design. *Mater. Des.*, **2015**, *86*, 902–912. https://doi.org/10.1016/j.matdes.2015.07.129.

[33] Sarina. What is TEXTILE? A simple guide to different types of textiles - Sew Guide https://sewguide.com/what-are-textiles/ (accessed Apr 10, 2021).

[34] Smith, A. Why 3D Printing is Important? https://dotslaz.com/why-3d-printing-is-important/ (accessed Dec 5, 2020).

[35] Brinks, G. J. (Ger); Warmoeskerken, M. M. C. G. (Marijn). The Added Value of 3D Polymer Deposition on Textiles. In *13th AUTEX World Textile Conference*; Saxion University of Applied Sciences, 2013; pp 1–6.

[36] Mather, R. R.; Wardman, R. H. *The Chemistry of Textile Fibre*, 2nd ed.; Royal Society of Chemistry, 2015.

[37] Balter, M. Clothes Make the (Hu) Man. *Science (80-.).*, **2009**, *325* (5946), 1329. https://doi.org/10.1126/science.325_1329a.

[38] Raichurkar, P.; Ramachandran, M. Recent Trends and Developments in Textile Industry in India. *Int. J. Text. Eng. Process.*, **2015**, *1* (4), 47–50.

[39] Robertson, J.; Roux, C.; Wiggins, K. G. *Forensic Examination of Fibres*, 3rd ed.; CRC Press, 2021.

[40] Humphries, M. *Fabric Reference: Pearson New International Edition*, 4th ed.; 2014.

[41] Carr, D. J. Fibres, Yarns and Fabrics. In *Forensic Textile Science*; Elsevier Inc., 2017; pp 3–14. https://doi.org/10.1016/B978-0-08-101872-9.00001-7.

[42] Pohl, G. *Textiles, Polymers and Composites for Buildings*; 2010. https://doi.org/10.1533/9780845699994.

[43] Sitotaw, D. B.; Ahrendt, D.; Kyosev, Y.; Kabish, A. K. Additive Manufacturing and Textiles—State-of-the-Art. *Appl. Sci.*, **2020**, *10* (15), 5033. https://doi.org/10.3390/app10155033.

[44] Gong, H.; Ozgen, B. *Fabric Structures: Woven, Knitted, or Nonwoven*; Elsevier Ltd., 2017. https://doi.org/10.1016/B978-0-08-101273-4.00007-X.

[45] Pei, E.; Shen, J.; Watling, J. Direct 3D Printing of Polymers onto Textiles: Experimental Studies and Applications. *Rapid Prototyp. J.*, **2015**, *21* (5), 556–571. https://doi.org/10.1108/RPJ-09-2014-

0126.

[46] Bonaldi, R. R. *Functional Finishes for High-Performance Apparel*; Elsevier Ltd., 2017. https://doi.org/10.1016/B978-0-08-100904-8.00006-7.

[47] Volkov, S. S. Production of Non-woven Materials by Fixing Fibre Lap Rolls Using Ultrasonic Welding. *Weld. Int.*, **2001**, *15* (9), 748–752. https://doi.org/10.1080/09507110109549437.

[48] Chakraborty, S.; Biswas, M. C. 3D Printing Technology of Polymer-Fiber Composites in Textile and Fashion Industry: A Potential Roadmap of Concept to Consumer. *Compos. Struct.*, **2020**, *248*, 112562. https://doi.org/10.1016/j.compstruct.2020.112562.

[49] Brooke, E. Why 3D Printing Will Work In Fashion https://techcrunch.com/2013/07/20/why-3d-printing-will-work-in-fashion/ (accessed Jun 12, 2021).

[50] Bingham, G. A.; Hague, R. J. M.; Tuck, C. J.; Long, A. C.; Crookston, J. J.; Sherburn, M. N. Rapid Manufactured Textiles. *Int. J. Comput. Integr. Manuf.*, **2007**, *20* (1), 96–105. https://doi.org/10.1080/09511920600690434.

[51] Gunay, M. *Eco-Friendly Textile Dyeing and Finishing*; Gunay, M., Ed.; IntechOpen, 2013. https://doi.org/10.5772/3436.

[52] Tyler, D. J. *Carr & Latham's Technology of Clothing Manufacture*, 4th ed.; Wiley-Blackwell, 2008.

[53] Coppage-Gross, J. *Textiles for Industrial Applications*; Taylor & Francis, 2016; Vol. 31. https://doi.org/10.1080/10426914.2015.1108805.

[54] McCarthy, B. J. *An Overview of the Technical Textiles Sector*, Second Edi.; Elsevier Ltd., 2016; Vol. 1. https://doi.org/10.1016/B978-1-78242-458-1.00001-7.

[55] Horrocks, A. R.; Anand, S. C. *Handbook of Technical Textiles*, 1st ed.; Woodhead Publishing Ltd., 2000.

[56] Syduzzaman, M.; Patwary, S.; Farhana, K.; Ahmed, S. Smart Textiles and Nano-Technology : A General Overview. *J. Text. Sci. Eng.*, **2015**, *5* (1), 1–7. https://doi.org/10.4172/2165-8064.1000181.

[57] Van Langenhove, L.; Hertleer, C. Smart Clothing: A New Life. *Int. J. Cloth. Sci. Technol.*, **2004**, *16* (1–2), 63–72. https://doi.org/10.1108/09556220410520360.

[58] Muhammad Sayem, A. S.; Hon Teay, S.; Shahariar, H.; Luise Fink, P.; Albarbar, A. Review on Smart Electro-Clothing Systems (SeCSs). *Sensors*, **2020**, *20* (3), 587. https://doi.org/10.3390/s20030587.

[59] Jeon, H.-Y. Polymeric Synthetic Fabrics to Improve Stability of Ground Structure in Civil Engineering Circumstance. In *Engineered Fabrics*; IntechOpen, 2019. https://doi.org/10.5772/intechopen.81246.

[60] Rohani Shirvan, A.; Nouri, A. Medical Textiles. In *Advances in Functional and Protective Textiles*; Elsevier, 2020; pp 291–333. https://doi.org/10.1016/B978-0-12-820257-9.00013-8.

[61] Bechtold, T.; Caven, B.; Wright, T. Sportswear for Snow Sports. In *Textiles for Sportswear*; Elsevier Inc., 2015; pp 245–265. https://doi.org/10.1016/B978-1-78242-229-7.00011-4.

[62] Daanen, H. Physiological Strain and Comfort in Sports Clothing. In *Textiles for Sportswear*; Elsevier Inc., 2015; pp 153–168. https://doi.org/10.1016/B978-1-78242-229-7.00007-2.

[63] Kurban, M.; Babaarslan, O.; Çağatay, İ. H. Hybrid Yarn Composites for Construction. In *Textiles for Advanced Applications*; InTech, 2017. https://doi.org/10.5772/intechopen.69034.

[64] Buhu, A.; Buhu, L. Woven Fabrics for Technical and Industrial Products. In *Textiles for Advanced Applications*; InTech, 2017. https://doi.org/10.5772/intechopen.68989.

[65] Stansbury, J. W.; Idacavage, M. J. 3D Printing with Polymers: Challenges among Expanding Options and Opportunities. *Dent. Mater.*, **2016**, *32* (1), 54–64. https://doi.org/10.1016/j.dental.2015.09.018.

[66] Gross, B. C.; Erkal, J. L.; Lockwood, S. Y.; Chen, C.; Spence, D. M. Evaluation of 3D Printing and Its Potential Impact on Biotechnology and the Chemical Sciences. *Anal. Chem.*, **2014**, *86* (7), 3240–3253. https://doi.org/10.1021/ac403397r.

[67] Luo, W.; Ma, X.; Yin, J. Application and Research on Building 3D Printing. *J. Crit. Rev.*, **2020**, *7* (12), 564–578. https://doi.org/http://dx.doi.org/10.31838/jcr.07.12.103.

[68] Korger, M.; Bergschneider, J.; Lutz, M.; Mahltig, B.; Finsterbusch, K.; Rabe, M. Possible Applications of 3D Printing Technology on Textile Substrates. *IOP Conf. Ser. Mater. Sci. Eng.*, **2016**, *141* (1). https://doi.org/10.1088/1757-899X/141/1/012011.

[69] Campbell, T.; Williams, C.; Ivanova, O.; Garrett, B. Could 3D Printing Change the World? http://www.atlanticcouncil.org/publications/reports/could-3d-printing-change-the-world (accessed Apr 10, 2021).

[70] Bechtold, S. *3D Printing and the Intellectual Property System*; Economics & Statistics; 28; 2015.

[71] Motadaka, S. A Review of 3D Printing Research from Computer and Information Science Perspective : Challenges and Research Directions, University at Buffalo, 2019.

[72] Weng, Z.; Wang, J.; Senthil, T.; Wu, L. Mechanical and Thermal Properties of ABS/Montmorillonite Nanocomposites for Fused Deposition Modeling 3D Printing. *Mater. Des.*, **2016**, *102*, 276–283. https://doi.org/10.1016/j.matdes.2016.04.045.

[73] Ursan, I.; Chiu, L.; Pierce, A. Three-Dimensional Drug Printing: A Structured Review. *J. Am. Pharm. Assoc.*, **2013**, *53* (2), 136–144. https://doi.org/10.1331/JAPhA.2013.12217.

[74] Peng, T. Analysis of Energy Utilization in 3D Printing Processes. **2016**, *40*, 62–67. https://doi.org/https://doi.org/10.1016/j.procir.2016.01.055.

[75] Sharma, S.; Goel, S. A. Three-Dimensional Printing and Its Future in Medical World. *Jounal Med. Res. Innov.*, **1989**, *3* (1), 1–8. https://doi.org/10.15419/jmri.141.Publication.

[76] Kanada, Y. Method of Designing, Partitioning, and Printing 3D Objects with Specified Printing Direction. In *Proceedings of ISFA2014, 2014 International Symposium on Flexible Automation*; ISCIE: Awaji-Island, Hyogo, Japan, 2014; pp 14–16.

[77] El-Dairi, M.; House, R. J. Optic Nerve Hypoplasia. *Handb. Pediatr. Retin. OCT Eye-Brain Connect.*, **2019**, 285–287. https://doi.org/10.1016/B978-0-323-60984-5.00062-7.

[78] Lopes, G. F. Exploração Dos Possibilidades Da Impressão 3D Na Construção, UNIVERSIDADE DO PORTO, 2016.

[79] Pereira, G. R.; Gasi, F.; Lourenço, S. R. Review , Analysis , and Classification of 3D Printing

Literature : Types of Research and Technology Benefits. *Int. J. Adv. Eng. Res. Sci.*, **2019**, *6* (6), 167–187. https://doi.org/https://dx.doi.org/10.22161/ijaers.6.6.17.

[80] Parker, C. J. The Human Acceptance of 3D Printing in Fashion Paradox: Is Mass Customisation a Bridge Too Far? *Adv. Manuf. Autom.*, **2016**, *113*, 372–379. https://doi.org/10.2495/IWAMA150431.

[81] Corral, L. C.; Walker, K. J. Exploring the Abilities of 3D Printing and Its Viability for Consumption in the Fashion Industry, University of Arkansas, Fayetteville, 2017.

[82] Attaran, M. The Rise of 3-D Printing: The Advantages of Additive Manufacturing over Traditional Manufacturing. *Bus. Horiz.*, **2017**, *60* (5), 677–688. https://doi.org/10.1016/j.bushor.2017.05.011.

[83] Perry, A. Consumers' Purchase Intention of 3D-Printed Apparel. *J. Glob. Fash. Mark.*, **2016**, *7* (4), 225–237. https://doi.org/10.1080/20932685.2016.1205953.

[84] Lyu, J.; Hahn, K.; Sadachar, A. Understanding Millennial Consumer's Adoption of 3D Printed Fashion Products by Exploring Personal Values and Innovativeness. *Fash. Text.*, **2018**, *5* (1). https://doi.org/10.1186/s40691-017-0119-8.

[85] Perry, A. Factors Comprehensively Influencing Acceptance of 3D-Printed Apparel. *J. Fash. Mark. Manag.*, **2017**, *21* (2), 219–234. https://doi.org/10.1108/JFMM-03-2016-0028.

[86] Perry, A. 3D-Printed Apparel and 3D-Printer: Exploring Advantages, Concerns, and Purchases. *Int. J. Fash. Des. Technol. Educ.*, **2018**, *11* (1), 95–103. https://doi.org/10.1080/17543266.2017.1306118.

[87] Petrovic, V.; Vicente Haro Gonzalez, J.; Jordá Ferrando, O.; Delgado Gordillo, J.; Ramon Blasco Puchades, J.; Portoles Grinan, L. Additive Layered Manufacturing: Sectors of Industrial Application Shown through Case Studies. *Int. J. Prod. Res.*, **2011**, *49* (4), 1061–1079. https://doi.org/10.1080/00207540903479786.

[88] Gebler, M.; Schoot Uiterkamp, A. J. M.; Visser, C. A Global Sustainability Perspective on 3D Printing Technologies. *Energy Policy*, **2014**, *74* (C), 158–167. https://doi.org/10.1016/j.enpol.2014.08.033.

[89] Yudhi, A. Facilitating Consumer Involvement in Design for Additive Manufacturing / 3D Printing Products, Loughborough University, 2016.

[90] Florida, R. The New Industrial Revolution. *Futures*, **1991**, *23* (6), 559–576. https://doi.org/10.1016/0016-3287(91)90079-H.

[91] Manyika, J.; Chui, M.; Bughin, J.; Dobbs, R.; Bisson, P.; Marrs, A. *Disruptive Technologies: Advances That Will Transform Life, Business, and the Global Economy*; 2013.

[92] Steenhuis, H.-J.; Pretorius, L. Consumer Additive Manufacturing or 3D Printing Adoption: An Exploratory Study. *J. Manuf. Technol. Manag.*, **2016**, *27* (7), 990–1012. https://doi.org/10.1108/JMTM-01-2016-0002.

[93] ISO/ASTM 52900:2015(en) Additive manufacturing — General principles — Terminology https://www.iso.org/obp/ui/#iso:std:iso-astm:52900:ed-1:v1:en (accessed Dec 25, 2020).

[94] Ahart, M. Types of 3D Printing Explained https://www.protolabs.com/resources/blog/types-of-3d-printing/ (accessed Nov 26, 2020).

[95] Research, G. V. 3D Printing Market Size, Share | Industry Report, 2021-2028 https://www.grandviewresearch.com/industry-analysis/3d-printing-industry-analysis (accessed Jun 13, 2021).

[96] Rosen, D. W. Computer-Aided Design for Additive Manufacturing of Cellular Structures. *Comput. Aided. Des. Appl.*, **2007**, *4* (5), 585–594. https://doi.org/10.1080/16864360.2007.10738493.

[97] Low, Z. X.; Chua, Y. T.; Ray, B. M.; Mattia, D.; Metcalfe, I. S.; Patterson, D. A. Perspective on 3D Printing of Separation Membranes and Comparison to Related Unconventional Fabrication Techniques. *J. Memb. Sci.*, **2017**, *523* (May 2016), 596–613. https://doi.org/10.1016/j.memsci.2016.10.006.

[98] Gokuldoss, P. K.; Kolla, S.; Eckert, J. Additive Manufacturing Processes: Selective Laser Melting, Electron Beam Melting and Binder Jetting-Selection Guidelines. *Materials (Basel).*, **2017**, *10* (6). https://doi.org/10.3390/ma10060672.

[99] Gibson, I.; Rosen, D.; Stucker, B. Introduction and Basic Principles. In *Additive Manufacturing Technologies*; Springer: Boston, 2010; pp 20–35. https://doi.org/10.1007/978-1-4939-2113-3_1.

[100] Mostafaei, A.; Elliott, A. M.; Barnes, J. E.; Li, F.; Tan, W.; Cramer, C. L.; Nandwana, P.; Chmielus, M. Binder Jet 3D Printing – Process Parameters, Materials, Properties, and Challenges. *Prog. Mater. Sci.*, **2020**, 10–11. https://doi.org/10.1016/j.pmatsci.2020.100707.

[101] Tofail, S. A. M.; Koumoulos, E. P.; Bandyopadhyay, A.; Bose, S.; O'Donoghue, L.; Charitidis, C. Additive Manufacturing: Scientific and Technological Challenges, Market Uptake and Opportunities. *Mater. Today*, **2018**, *21* (1), 22–37. https://doi.org/10.1016/j.mattod.2017.07.001.

[102] Dutta, B.; Froes, F. H. (Sam). The Additive Manufacturing (AM) of Titanium Alloys. *Met. Powder Rep.*, **2017**, *72* (2), 96–106. https://doi.org/10.1016/j.mprp.2016.12.062.

[103] Kaynak, B.; Spoerk, M.; Shirole, A.; Ziegler, W.; Sapkota, J. Polypropylene/Cellulose Composites for Material Extrusion Additive Manufacturing. *Macromol. Mater. Eng.*, **2018**, *303* (5), 1–8. https://doi.org/10.1002/mame.201800037.

[104] Braconnier, D. J.; Jensen, R. E.; Peterson, A. M. Processing Parameter Correlations in Material Extrusion Additive Manufacturing. *Addit. Manuf.*, **2020**, *31*, 100924. https://doi.org/10.1016/j.addma.2019.100924.

[105] Yap, Y. L.; Wang, C.; Sing, S. L.; Dikshit, V.; Yeong, W. Y.; Wei, J. Material Jetting Additive Manufacturing: An Experimental Study Using Designed Metrological Benchmarks. *Precis. Eng.*, **2017**, *50*, 275–285. https://doi.org/10.1016/j.precisioneng.2017.05.015.

[106] Arrillaga, M. B.; Taha, I. A Review of Additive Manufacturing Technologies and Markets for Thermosetting Resins and Their Potential for Carbon Fiber Integration. *Addit. Manuf.*, **2021**, *37* (December 2020), 101748. https://doi.org/10.1016/j.addma.2020.101748.

[107] Tiwari, S. K.; Pande, S.; Agrawal, S.; Bobade, S. M. Selection of Selective Laser Sintering Materials for Different Applications. *Rapid Prototyp. J.*, **2015**, *21* (6), 630–648. https://doi.org/10.1108/RPJ-03-2013-0027.

[108] Chang, B.; Parandoush, P.; Li, X.; Ruan, S.; Shen, C.; Behnagh, R. A.; Liu, Y.; Lin, D. Ultrafast Printing of Continuous Fiber-reinforced Thermoplastic Composites with Ultrahigh Mechanical Performance by Ultrasonic-assisted Laminated Object Manufacturing. *Polym. Compos.*, **2020**, *41*

(11), 4706–4715. https://doi.org/10.1002/pc.25744.

[109] Molitch-Hou, M. Overview of Additive Manufacturing Process. In *Additive Manufacturing*; Zhang, J., Jung, Y.-G., Eds.; Elsevier Inc., 2018; pp 1–38. https://doi.org/https://doi.org/10.1016/B978-0-12-812155-9.00001-3.

[110] Brown, J. H.; Colton, J. S. A Machine System for the Rapid Production of Composite Structures. *Polym. Compos.*, **2000**, *21* (1), 124–133. https://doi.org/10.1002/pc.10171.

[111] Bikas, H.; Stavropoulos, P.; Chryssolouris, G. Additive Manufacturing Methods and Modeling Approaches: A Critical Review. *Int. J. Adv. Manuf. Technol.*, **2016**, *83* (1–4), 389–405. https://doi.org/10.1007/s00170-015-7576-2.

[112] Gibson, I.; Rosen, D.; Stucker, B. *Additive Manufacturing Technologies*, 2nd ed.; Springer-Verlag New York, 2015. https://doi.org/10.1007/978-1-4939-2113-3.

[113] Too, M. H.; Leong, K. F.; Chua, C. K.; Du, Z. H.; Yang, S. F.; Cheah, C. M.; Ho, S. L. Investigation of 3D Non-Random Porous Structures by Fused Deposition Modelling. *Int. J. Adv. Manuf. Technol.*, **2002**, *19* (3), 217–223. https://doi.org/10.1007/s001700200016.

[114] Agarwala, M. K.; Jamalabad, V. R.; Langrana, N. A.; Safari, A.; Whalen, P. J.; Danforth, S. C. Structural Quality of Parts Processed by Fused Deposition. *Rapid Prototyp. J.*, **1996**, *2* (4), 4–19. https://doi.org/https://doi.org/10.1108/13552549610732034.

[115] Carneiro, O. S.; Silva, A. F.; Gomes, R. Fused Deposition Modeling with Polypropylene. *Mater. Des.*, **2015**, *83*, 768–776. https://doi.org/10.1016/j.matdes.2015.06.053.

[116] MakerBot. MakerBot® Announces New Replicator™ 2 & 2X Desktop 3D Printers, A New York MakerBot Store, New Software, and More https://www.businesswire.com/news/home/20120919006590/en/MakerBot&reg (accessed Jun 12, 2021).

[117] MakerBot. MakerBot and Designer Francis Bitonti Collaborate on New Skins Workshop To Create Fabulous 3D Printed Dress https://www.businesswire.com/news/home/20140312006034/en/MakerBot-Designer-Francis-Bitonti-Collaborate-Skins-Workshop (accessed Jun 12, 2021).

[118] Reilly, L. The Shift from 3D Body Scanned Data to the Physical World. In *Shapeshifting: A Conference on Transformative Paradigms of Fashion and Textile Design*; Textile and Design Lab and Colab at Auckland University of Technology: Auckland, 2014; pp 1–18.

[119] MakerBot. MakerBot Explorers | Francis Bitonti's New Skins https://www.makerbot.com/stories/design/makerbot-explorers-francis-bitontis-new-skins/ (accessed Jun 12, 2021).

[120] Ishack, S.; Lipner, S. R. Applications of 3D Printing Technology to Address COVID-19–Related Supply Shortages. *American Journal of Medicine*. Elsevier Inc. July 1, 2020, pp 771–773. https://doi.org/10.1016/j.amjmed.2020.04.002.

[121] MaterialDistrict. 3D Printed Surface https://materialdistrict.com/material/3d-printed-surface/#moved (accessed Jun 12, 2021).

[122] What is Nike Flyprint?-Nike News https://news.nike.com/news/nike-flyprint-3d-printed-textile

(accessed Jun 12, 2021).

[123] Ding, R.; Du, Y.; Goncalves, R. B.; Francis, L. F.; Reineke, T. M. Sustainable near UV-Curable Acrylates Based on Natural Phenolics for Stereolithography 3D Printing. *Polym. Chem.*, **2019**, *10* (9), 1067–1077. https://doi.org/10.1039/c8py01652f.

[124] Cooke, M. N.; Fisher, J. P.; Dean, D.; Rimnac, C.; Mikos, A. G. Use of Stereolithography to Manufacture Critical-Sized 3D Biodegradable Scaffolds for Bone Ingrowth. *J. Biomed. Mater. Res. - Part B Appl. Biomater.*, **2003**, *64* (2), 65–69. https://doi.org/10.1002/jbm.b.10485.

[125] Han, D.; Lu, Z.; Chester, S. A.; Lee, H. Micro 3D Printing of a Temperature-Responsive Hydrogel Using Projection Micro-Stereolithography. *Sci. Rep.*, **2018**, *8* (1), 1–10. https://doi.org/10.1038/s41598-018-20385-2.

[126] Iris van Herpen Debuts Wearable 3D Printed Pieces at Paris Fashion Week https://www.materialise.com/en/cases/iris-van-herpen-debuts-wearable-3d-printed-pieces-at-paris-fashion-week (accessed Jun 12, 2021).

[127] Materialise. Stereolithography | SLA | 3D Printing at Materialise https://www.materialise.com/en/manufacturing/3d-printing-technology/stereolithography (accessed Jun 12, 2021).

[128] Das, S. Physical Aspects of Process Control in Selective Laser Sintering of Metals. *Adv. Eng. Mater.*, **2003**, *5* (10), 701–711. https://doi.org/10.1002/adem.200310099.

[129] Kruth, J. P.; Mercelis, P.; Van Vaerenbergh, J.; Froyen, L.; Rombouts, M. Binding Mechanisms in Selective Laser Sintering and Selective Laser Melting. *Rapid Prototyp. J.*, **2005**, *11* (1), 26–36. https://doi.org/10.1108/13552540510573365.

[130] Kruth, J. P.; Wang, X.; Laoui, T.; Froyen, L. Lasers and Materials in Selective Laser Sintering. *Assem. Autom.*, **2003**, *23* (4), 357–371. https://doi.org/10.1108/01445150310698652.

[131] Yadroitsev, I.; Bertrand, P.; Smurov, I. Parametric Analysis of the Selective Laser Melting Process. *Appl. Surf. Sci.*, **2007**, *253* (19), 8064–8069. https://doi.org/10.1016/j.apsusc.2007.02.088.

[132] Saunders, S. Sinterit's SLS 3D Printing and Flexible Materials Used to Make Strong Textiles for Opera Costumes - 3DPrint.com | The Voice of 3D Printing / Additive Manufacturing https://3dprint.com/237610/sinterit-flexible-strong-textiles-for-opera-costumes/ (accessed Jun 12, 2021).

[133] Digits2Widgets. Flexible 3D Printed SLS "Fabrics" Developed by D2W https://www.digits2widgets.com/3d-printing-portfolio/nylon-sls-fabrics/ (accessed Jun 12, 2021).

[134] Cuzella, J. Fast Fashion: A Proposal for Copyright Protection of 3D-Printed Apparel. *Color. Technol. Law J.*, **2015**, *13* (2), 369–392.

[135] Hennessey, R. 3D Printing Hits The Fashion World https://www.forbes.com/sites/rachelhennessey/2013/08/07/3-d-printed-clothes-could-be-the-next-big-thing-to-hit-fashion/?sh=af126d066f22 (accessed Jun 12, 2021).

[136] Nayak, R.; Padhye, R. Introduction: The Apparel Industry. The Apparel Industry. In *Garment Manufacturing Technology*; Elsevier, 2015; pp 1–17. https://doi.org/10.1016/B978-1-78242-232-7.00001-1.

[137] Fitzgerald, M. With 3-D Printing, the Shoe Really Fits https://sloanreview.mit.edu/article/with-3-d-printing-the-shoe-really-fits/?utm_source=twitter&utm_medium=social&utm_campaign=sm-direct (accessed Jun 12, 2021).

[138] Nike debuts first-ever football cleat built using 3D printing technology - Nike News https://news.nike.com/news/nike-tech-pack-fall-2018 (accessed Jun 12, 2021).

[139] Park, J.; Tari, M. J.; Hahn, H. T. Characterization of the Laminated Object Manufacturing (LOM) Process. *Rapid Prototyp. J.*, **2000**, *6* (1), 36–49. https://doi.org/10.1108/13552540010309868.

[140] Tari, M. J.; Bals, A.; Park, J.; Lin, M. Y.; Thomas, H. Rapid Prototyping of Composite Parts Using Resin Transfer Molding and Laminated Object Manufacturing. *Compos. Part A Appl. Sci. Manuf.*, **1998**, *29* (5–6), 651–661. https://doi.org/https://doi.org/10.1016/S1359-835X(97)00113-9.

[141] Liu, S.; Ye, F.; Liu, L.; Liu, Q. Feasibility of Preparing of Silicon Nitride Ceramics Components by Aqueous Tape Casting in Combination with Laminated Object Manufacturing. *Mater. Des.*, **2015**, *66* (PA), 331–335. https://doi.org/10.1016/j.matdes.2014.10.079.

[142] Paul, B. K.; Voorakarnam, V. Effect of Layer Thickness and Orientation Angle on Surface Roughness in Laminated Object Manufacturing. *J. Manuf. Process.*, **2001**, *3* (2), 94–101. https://doi.org/10.1016/S1526-6125(01)70124-7.

[143] Mu, Q.; Wang, L.; Dunn, C. K.; Kuang, X.; Duan, F.; Zhang, Z.; Qi, H. J.; Wang, T. Digital Light Processing 3D Printing of Conductive Complex Structures. *Addit. Manuf.*, **2017**, *18*, 74–83. https://doi.org/https://doi.org/10.1016/j.addma.2017.08.011.

[144] Xue, D.; Wang, Y.; Mei, D. Multi-Step Exposure Method for Improving Structure Flatness in Digital Light Processing-Based Printing. *J. Manuf. Process.*, **2019**, *39* (July 2018), 106–113. https://doi.org/10.1016/j.jmapro.2019.02.013.

[145] Kowsari, K.; Akbari, S.; Wang, D.; Fang, N. X.; Ge, Q. High-Efficiency High-Resolution Multimaterial Fabrication for Digital Light Processing-Based Three-Dimensional Printing. *3D Print. Addit. Manuf.*, **2018**, *5* (3), 185–193. https://doi.org/10.1089/3dp.2018.0004.

[146] Tiller, B.; Reid, A.; Zhu, B.; Guerreiro, J.; Domingo-Roca, R.; Curt Jackson, J.; Windmill, J. F. C. Piezoelectric Microphone via a Digital Light Processing 3D Printing Process. *Mater. Des.*, **2019**, *165*, 107593. https://doi.org/10.1016/j.matdes.2019.107593.

[147] Kim, S. G.; Song, J. E.; Kim, H. R. Development of Fabrics by Digital Light Processing Three-Dimensional Printing Technology and Using a Polyurethane Acrylate Photopolymer. *Text. Res. J.*, **2020**, *90* (7–8), 847–856. https://doi.org/10.1177/0040517519881821.

[148] Mei, J.; Lovell, M. R.; Mickle, M. H. Formulation and Processing of Novel Conductive Solution Inks in Continuous Inkjet Printing of 3-D Electric Circuits. *IEEE Trans. Electron. Packag. Manuf.*, **2005**, *28* (3), 265–273. https://doi.org/10.1109/TEPM.2005.852542.

[149] Derby, B. Additive Manufacture of Ceramics Components by Inkjet Printing. *Engineering*, **2015**, *1* (1), 113–123. https://doi.org/10.15302/J-ENG-2015014.

[150] Continuous Inkjet Printing | OLED Printing Industry https://www.flow3d.com/continuous-inkjet-printing/ (accessed Feb 24, 2021).

[151] Pinargote, N. W. S.; Smirnov, A.; Peretyagin, N.; Seleznev, A.; Peretyagin, P. Direct Ink Writing

Technology (3d Printing) of Graphene-based Ceramic Nanocomposites: A Review. *Nanomaterials*, **2020**, *10* (7), 1–48. https://doi.org/10.3390/nano10071300.

[152] Kaempfer, N. Ganit Goldstein teams up with Stratasys to achieve her mission of customized fashion design https://www.stratasys.com/explore/blog/2020/direct-to-textile-3d-printing (accessed Jun 16, 2021).

[153] Kabir, S. M. F.; Mathur, K.; Seyam, A.-F. M. Impact Resistance and Failure Mechanism of 3D Printed Continuous Fiber-Reinforced Cellular Composites. *J. Text. Inst.*, **2021**, *112* (5), 1–10. https://doi.org/10.1080/00405000.2020.1778223.

[154] Gershenfeld, N. How to Make Almost Anything: The Digital Fabrication Revolution. *Foreign Aff.*, **2012**, *91* (6), 43–57.

[155] Taylor, A.; Unver, E.; Worth, G. Innovative Potential of 3D Software Applications in Fashion and Textile Design. *Digit. Creat.*, **2003**, *14* (4), 211–218. https://doi.org/10.1076/digc.14.4.211.27880.

[156] Istook, C. L.; Newcomb, E. A.; Lim, H. Three-Dimensional (3D) Technologies for Apparel and Textile Design. In *Computer Technology for Textiles and Apparel*; Elsevier, 2011; pp 296–325. https://doi.org/10.1533/9780857093608.3.296.

[157] CLO | 3D Fashion Design Software https://www.clo3d.com/ (accessed Jun 11, 2021).

[158] Advanced 2D and 3D patternmaking and prototyping software | Lectra https://www.lectra.com/en/products/modaris-expert (accessed Jun 11, 2021).

[159] Optitex. Fashion Design Software | 2D/3D CAD CAM https://optitex.com/ (accessed Jun 11, 2021).

[160] Printing.com, 3D. Software for 3D Printing - 3D Modeling Software/Slicers/3D Printer Hosts https://3dprinting.com/software/ (accessed Jun 9, 2021).

[161] Rahiminia, M. A.; Latifi, M.; Sadighi, M. Analysis of Longitudinal and Innovative Transversal 3D Printed Lattice Tubular Braid Textures Subjected to Internal Compression as Reinforcement. *J. Ind. Text.*, **2020**. https://doi.org/10.1177/1528083720912213.

[162] Autodesk. Fusion 360 | 3D CAD, CAM, CAE & PCB Cloud-Based Software https://www.autodesk.com/products/fusion-360/overview?term=1-YEAR (accessed Jun 11, 2021).

[163] Autodesk. Maya Software | Get Prices & Buy Official Maya 2022 https://www.autodesk.com/products/maya/overview?term=1-YEAR#maya-intro (accessed Jun 11, 2021).

[164] Verma, A. Blender: 3D Print Toolbox – Simply Explained https://all3dp.com/2/blender-3d-print-toolbox-simply-explained/ (accessed Jun 11, 2021).

[165] SOLIDWORKS 3D CAD | SOLIDWORKS https://www.solidworks.com/product/solidworks-3d-cad (accessed Jun 11, 2021).

[166] Rhinoceros. Rhino - Features https://www.rhino3d.com/features/ (accessed Jun 11, 2021).

[167] Melnikova, R.; Ehrmann, A.; Finsterbusch, K. 3D Printing of Textile-Based Structures by Fused Deposition Modelling (FDM) with Different Polymer Materials. *IOP Conf. Ser. Mater. Sci. Eng.*,

2014, *62* (1). https://doi.org/10.1088/1757-899X/62/1/012018.

[168] Letcher, T. Material Property Testing of 3D-Printed Specimen in PLA on an Entry-Level 3D Printer. In *ASME 2014 International Mechanical Engineering Congress and Exposition*; Montreal, Quebec, Canada, 2016; pp 1–8. https://doi.org/https://doi.org/10.1115/IMECE2014-39379.

[169] Cura, U. Powerful, easy-to-use 3D printing software https://ultimaker.com/software/ultimaker-cura (accessed Jun 10, 2021).

[170] Simplify3D. Professional 3D Printing Software https://www.simplify3d.com/ (accessed Jun 11, 2021).

[171] Slic3r. Open source 3D printing toolbox https://slic3r.org/ (accessed Jun 11, 2021).

[172] Grothe, T.; Brockhagen, B.; Storck, J. L. Three-Dimensional Printing Resin on Different Textile Substrates Using Stereolithography: A Proof of Concept. *J. Eng. Fiber. Fabr.*, **2020**, *15*. https://doi.org/10.1177/1558925020933440.

[173] Fernandez-Vicente, M.; Calle, W.; Ferrandiz, S.; Conejero, A. Effect of Infill Parameters on Tensile Mechanical Behavior in Desktop 3D Printing. *3D Print. Addit. Manuf.*, **2016**, *3* (3), 183–192. https://doi.org/10.1089/3dp.2015.0036.

[174] Korger, M.; Glogowsky, A.; Sanduloff, S.; Steinem, C.; Huysman, S.; Horn, B.; Ernst, M.; Rabe, M. Testing Thermoplastic Elastomers Selected as Flexible Three-Dimensional Printing Materials for Functional Garment and Technical Textile Applications. *J. Eng. Fiber. Fabr.*, **2020**, *15*. https://doi.org/10.1177/1558925020924599.

[175] Mpofu, N. S.; Mwasiagi, J. I.; Nkiwane, L. C.; Githinji, D. N. The Use of Statistical Techniques to Study the Machine Parameters Affecting the Properties of 3D Printed Cotton/Polylactic Acid Fabrics. *J. Eng. Fiber. Fabr.*, **2020**, *15*. https://doi.org/10.1177/1558925020928531.

[176] Flores-Hernandez, C. G.; Velasco-Santos, C.; Hernandez-Zea, A. L.; Gomez-Guzman, O.; Yañez-Limon, J. M.; Rivera-Armenta, J. L.; Martinez-Hernandez, A. L. Low Concentrations for Significant Improvements in Thermal and Thermomechanical Properties of Poly(Lactic Acid)–Keratin Biocomposites Obtained by Extrusion and 3D Printing. *J. Nat. Fibers*, **2020**. https://doi.org/10.1080/15440478.2020.1788483.

[177] Carolo, L. Tinkercad Tutorial: Get Started with 6 Easy Steps https://all3dp.com/2/tinkercad-tutorial-easy-beginners/ (accessed Jun 11, 2021).

[178] Tinkercad | Create 3D digital designs with online CAD | Tinkercad https://www.tinkercad.com/ (accessed Jun 11, 2021).

[179] Kabir, S.; Kim, H.; Lee, S. Physical Property of 3D-Printed Sinusoidal Pattern Using Shape Memory TPU Filament. *Text. Res. J.*, **2020**, *90* (21–22), 2399–2410. https://doi.org/10.1177/0040517520919750.

[180] Bodkhe, S.; Ermanni, P. 3D Printing of Multifunctional Materials for Sensing and Actuation : Merging Piezoelectricity with Shape Memory. *Eur. Polym. J.*, **2020**, *132* (May), 109738. https://doi.org/10.1016/j.eurpolymj.2020.109738.

[181] Graßmann, C.; Grethe, T.; Langenhove, L. Van; Schwarz-pfeiffer, A. Digital Printing of Electroluminescent Devices on Textile Substrates. *J. Eng. Fiber. Fabr.*, **2019**, *14* (1).

https://doi.org/10.1177/1558925019861624.

[182] Repetier. Slicer Software https://www.repetier.com/ (accessed Jun 11, 2021).

[183] OctoPrint.org. Slicer Software https://octoprint.org/ (accessed Jun 11, 2021).

[184] KISSlicer. Slicer Software https://www.kisslicer.com/ (accessed Jun 11, 2021).

[185] Beecroft, M. Digital Interlooping: 3D Printing of Weft-Knitted Textile-Based Tubular Structures Using Selective Laser Sintering of Nylon Powder. *Int. J. Fash. Des. Technol. Educ.*, **2019**, *12* (2), 218–224. https://doi.org/10.1080/17543266.2019.1573269.

[186] Yap, Y. L.; Yeong, W. Y. Additive Manufacture of Fashion and Jewellery Products: A Mini Review: This Paper Provides an Insight into the Future of 3D Printing Industries for Fashion and Jewellery Products. *Virtual Phys. Prototyp.*, **2014**, *9* (3), 195–201. https://doi.org/10.1080/17452759.2014.938993.

[187] Gopi, S.; Balakrishnan, P.; Chandradhara, D.; Poovathankandy, D.; Thomas, S. General Scenarios of Cellulose and Its Use in the Biomedical Field. *Mater. Today Chem.*, **2019**, *13*, 59–78. https://doi.org/10.1016/j.mtchem.2019.04.012.

[188] Starr, T. *Composites - A Profile of the World-Wide Reinforced Plastics Industry, Markets and Suppliers to 2005*, 3rd ed.; Elsevier Inc, 1999.

[189] Nikzad, M.; Masood, S. H.; Sbarski, I. Thermo-Mechanical Properties of a Highly Filled Polymeric Composites for Fused Deposition Modeling. *Mater. Des.*, **2011**, *32* (6), 3448–3456. https://doi.org/10.1016/j.matdes.2011.01.056.

[190] Håkansson, K. M. O.; Henriksson, I. C.; de la Peña Vázquez, C.; Kuzmenko, V.; Markstedt, K.; Enoksson, P.; Gatenholm, P. Solidification of 3D Printed Nanofibril Hydrogels into Functional 3D Cellulose Structures. *Adv. Mater. Technol.*, **2016**, *1* (7), 1600096. https://doi.org/10.1002/admt.201600096.

[191] Huber, T.; Müssig, J.; Curnow, O.; Pang, S.; Bickerton, S.; Staiger, M. P. A Critical Review of All-Cellulose Composites. *J. Mater. Sci.*, **2012**, *47* (3), 1171–1186. https://doi.org/10.1007/s10853-011-5774-3.

[192] Oprea, M.; Voicu, S. I. Recent Advances in Composites Based on Cellulose Derivatives for Biomedical Applications. *Carbohydrate Polymers*. Elsevier Ltd November 2020, p 116683. https://doi.org/10.1016/j.carbpol.2020.116683.

[193] Palaganas, N. B.; Mangadlao, J. D.; De Leon, A. C. C.; Palaganas, J. O.; Pangilinan, K. D.; Lee, Y. J.; Advincula, R. C. 3D Printing of Photocurable Cellulose Nanocrystal Composite for Fabrication of Complex Architectures via Stereolithography. *ACS Appl. Mater. Interfaces*, **2017**, *9* (39), 34314–34324. https://doi.org/10.1021/acsami.7b09223.

[194] Long, H.; Wu, Z.; Dong, Q.; Shen, Y.; Zhou, W.; Luo, Y.; Zhang, C.; Dong, X. Mechanical and Thermal Properties of Bamboo Fiber Reinforced Polypropylene/Polylactic Acid Composites for 3D Printing. *Polym. Eng. Sci.*, **2019**, *59* (s2), E247–E260. https://doi.org/10.1002/pen.25043.

[195] Le Duigou, A.; Castro, M.; Bevan, R.; Martin, N. 3D Printing of Wood Fibre Biocomposites: From Mechanical to Actuation Functionality. *Mater. Des.*, **2016**, *96*, 106–114. https://doi.org/10.1016/j.matdes.2016.02.018.

[196] Tamicare. Welcome to a new genenration of fabric https://www.tamicare.com/ (accessed Jun 12, 2021).

[197] Kumar, S.; Singh, R.; Singh, T. P.; Batish, A. Investigations of Polylactic Acid Reinforced Composite Feedstock Filaments for Multimaterial Three-Dimensional Printing Applications. In *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science*; SAGE Publications Ltd, 2019; Vol. 233, pp 5953–5965. https://doi.org/10.1177/0954406219861665.

[198] Narula, A.; Pastore, C. M.; Schmelzeisen, D.; El Basri, S.; Schenk, J.; Shajoo, S. Effect of Knit and Print Parameters on Peel Strength of Hybrid 3-D Printed Textiles. *J. Text. Fibrous Mater.*, **2018**, *1*, 251522111774925. https://doi.org/10.1177/2515221117749251.

[199] Martens, Y.; Ehrmann, A. Composites of 3D-Printed Polymers and Textile Fabrics∗. *IOP Conf. Ser. Mater. Sci. Eng.*, **2017**, *225* (1). https://doi.org/10.1088/1757-899X/225/1/012292.

[200] Grain, E. 3D Printing Fashion With Recycled Polyester: A Sustainable Journey. In *IFFTI - BIFT 2016 International Conference*; University of Huddersfield: Beijing BIFT, 2016; p 23.

[201] Dawoud, M.; Taha, I.; Ebeid, S. J. Mechanical Behaviour of ABS: An Experimental Study Using FDM and Injection Moulding Techniques. *J. Manuf. Process.*, **2016**, *21*, 39–45. https://doi.org/10.1016/j.jmapro.2015.11.002.

[202] Tekinalp, H. L.; Kunc, V.; Velez-Garcia, G. M.; Duty, C. E.; Love, L. J.; Naskar, A. K.; Blue, C. A.; Ozcan, S. Highly Oriented Carbon Fiber-Polymer Composites via Additive Manufacturing. *Compos. Sci. Technol.*, **2014**, *105*, 144–150. https://doi.org/10.1016/j.compscitech.2014.10.009.

[203] Rocha, C. R.; Torrado Perez, A. R.; Roberson, D. A.; Shemelya, C. M.; Macdonald, E.; Wicker, R. B. Novel ABS-Based Binary and Ternary Polymer Blends for Material Extrusion 3D Printing. *J. Mater. Res.*, **2014**, *29* (17), 1859–1866. https://doi.org/10.1557/jmr.2014.158.

[204] Partsch, L.; Vassiliadis, S.; Papageorgas, P. 3D Printed Textile Fabrics Structures. In *5th International Istanbul Textile Congress 2015: Innovative Technologies "Inspire to Innovate";* Istanbul, 2015; pp 3–10.

[205] Chong, S.; Pan, G. T.; Khalid, M.; Yang, T. C. K.; Hung, S. T.; Huang, C. M. Physical Characterization and Pre-Assessment of Recycled High-Density Polyethylene as 3D Printing Material. *J. Polym. Environ.*, **2017**, *25* (2), 136–145. https://doi.org/10.1007/s10924-016-0793-4.

[206] Gao, T.; Yang, Z.; Chen, C.; Li, Y.; Fu, K.; Dai, J.; Hitz, E. M.; Xie, H.; Liu, B.; Song, J.; et al. Three-Dimensional Printed Thermal Regulation Textiles. *ACS Nano*, **2017**, *11* (11), 11513–11520. https://doi.org/10.1021/acsnano.7b06295.

[207] Gao, T.; Yang, Z.; Chen, C.; Li, Y.; Fu, K.; Dai, J.; Hitz, E. M.; Xie, H.; Liu, B.; Song, J.; et al. Three-Dimensional Printed Thermal Regulation Textiles. *ACS Nano*, **2017**, *11* (11), 11513–11520. https://doi.org/10.1021/acsnano.7b06295.

[208] Gnanasekaran, K.; Heijmans, T.; van Bennekom, S.; Woldhuis, H.; Wijnia, S.; de With, G.; Friedrich, H. 3D Printing of CNT- and Graphene-Based Conductive Polymer Nanocomposites by Fused Deposition Modeling. *Appl. Mater. Today*, **2017**, *9*, 21–28. https://doi.org/10.1016/j.apmt.2017.04.003.

[209] Chizari, K.; Daoud, M. A.; Ravindran, A. R.; Therriault, D. 3D Printing of Highly Conductive Nanocomposites for the Functional Optimization of Liquid Sensors. *Small*, **2016**, *12* (44), 6076–

6082. https://doi.org/10.1002/smll.201601695.

[210] Dopke, C.; Grimmelsmann, N.; Ehrmann, A. 3D Printing on Knitted Fabrics. In *48th IFKT Congress*; Mönchengladbach, Germany, 2017; pp 97–98.

[211] Kozior; Trabelsi; Mamun; Sabantina; Ehrmann. Stabilization of Electrospun Nanofiber Mats Used for Filters by 3D Printing. *Polymers (Basel).*, **2019**, *11* (10), 1618. https://doi.org/10.3390/polym11101618.

[212] Alagirusamy, R.; Fangueiro, R.; Ogale, V.; Padaki, N. Hybrid Yarns and Textile Preforming for Thermoplastic Composites. *Text. Prog.*, **2006**, *38* (4), 1–71. https://doi.org/10.1533/tepr.2006.0004.

[213] Hufenbach, W.; Böhm, R.; Thieme, M.; Winkler, A.; Mäder, E.; Rausch, J.; Schade, M. Polypropylene/Glass Fibre 3D-Textile Reinforced Composites for Automotive Applications. *Mater. Des.*, **2011**, *32* (3), 1468–1476. https://doi.org/10.1016/j.matdes.2010.08.049.

[214] Bilisik, K.; Kaya, G.; Ozdemir, H.; Korkmaz, M.; Erdogan, G. Applications of Glass Fibers in 3D Preform Composites. In *Advances in Glass Science and Technology*; IntechOpen, 2018. https://doi.org/10.5772/intechopen.73293.

[215] Sayilan, A.; Kaynan, Ö.; Yusifova, A.; Cebeci, H.; Yenigün, E. Ö. Design and Development of 3D Printed High Performance Textile Structures for Composites. *Tekst. ve Muhendis*, **2017**, *24* (105), 13–17. https://doi.org/10.7216/1300759920172410502.

[216] Szykiedans, K.; Credo, W. Mechanical Properties of FDM and SLA Low-Cost 3-D Prints. In *Procedia Engineering*; Elsevier Ltd, 2016; Vol. 136, pp 257–262. https://doi.org/10.1016/j.proeng.2016.01.207.

[217] Li, N.; Link, G.; Jelonnek, J. 3D Microwave Printing Temperature Control of Continuous Carbon Fiber Reinforced Composites. *Compos. Sci. Technol.*, **2020**, *187*, 107939. https://doi.org/10.1016/j.compscitech.2019.107939.

[218] Li, N.; Li, Y.; Liu, S. Rapid Prototyping of Continuous Carbon Fiber Reinforced Polylactic Acid Composites by 3D Printing. *J. Mater. Process. Technol.*, **2016**, *238*, 218–225. https://doi.org/10.1016/j.jmatprotec.2016.07.025.

[219] Yao, X.; Luan, C.; Zhang, D.; Lan, L.; Fu, J. Evaluation of Carbon Fiber-Embedded 3D Printed Structures for Strengthening and Structural-Health Monitoring. *Mater. Des.*, **2017**, *114*, 424–432. https://doi.org/10.1016/j.matdes.2016.10.078.

[220] Hashemi Sanatgar, R.; Cayla, A.; Campagne, C.; Nierstrasz, V. Manufacturing of Polylactic Acid Nanocomposite 3D Printer Filaments for Smart Textile Applications. In *IOP Conference Series: Materials Science and Engineering*; Institute of Physics Publishing, 2017; Vol. 254, p 072011. https://doi.org/10.1088/1757-899X/254/7/072011.

[221] van de Werken, N.; Tekinalp, H.; Khanbolouki, P.; Ozcan, S.; Williams, A.; Tehrani, M. Additively Manufactured Carbon Fiber-Reinforced Composites: State of the Art and Perspective. *Addit. Manuf.*, **2020**, *31*, 100962. https://doi.org/10.1016/j.addma.2019.100962.

[222] Hao, W.; Liu, Y.; Zhou, H.; Chen, H.; Fang, D. Preparation and Characterization of 3D Printed Continuous Carbon Fiber Reinforced Thermosetting Composites. *Polym. Test.*, **2018**, *65*, 29–34. https://doi.org/10.1016/j.polymertesting.2017.11.004.

[223] Ming, Y.; Duan, Y.; Wang, B.; Xiao, H.; Zhang, X. A Novel Route to Fabricate High-Performance 3D Printed Continuous Fiber-Reinforced Thermosetting Polymer Composites. *Materials (Basel).*, **2019**, *12* (9). https://doi.org/10.3390/ma12091369.

[224] Kabir, S. M. F.; Mathur, K.; Seyam, A. F. M. A Critical Review on 3D Printed Continuous Fiber-Reinforced Composites: History, Mechanism, Materials and Properties. *Composite Structures*. Elsevier Ltd January 15, 2020, p 111476. https://doi.org/10.1016/j.compstruct.2019.111476.

[225] Bettini, P.; Alitta, G.; Sala, G.; Di Landro, L. Fused Deposition Technique for Continuous Fiber Reinforced Thermoplastic. *J. Mater. Eng. Perform.*, **2017**, *26* (2), 843–848. https://doi.org/10.1007/s11665-016-2459-8.

[226] Caminero, M. A.; Chacón, J. M.; García-Moreno, I.; Reverte, J. M. Interlaminar Bonding Performance of 3D Printed Continuous Fibre Reinforced Thermoplastic Composites Using Fused Deposition Modelling. *Polym. Test.*, **2018**, *68*, 415–423. https://doi.org/10.1016/j.polymertesting.2018.04.038.

[227] Ma, L.; Wu, L.; Cheng, X.; Zhuo, D.; Weng, Z.; Wang, R. Improving the Interlaminar Properties of Polymer Composites Using a Situ Accumulation Method to Construct the Multi-Scale Reinforcement of Carbon Nanofibers/Carbon Fibers. *Compos. Part A Appl. Sci. Manuf.*, **2015**, *72*, 65–74. https://doi.org/10.1016/j.compositesa.2015.01.023.

[228] Gebhardt, A.; Hötter, J.-S. Rapid Prototyping. In *Additive Manufacturing*; Carl Hanser Verlag GmbH & Co. KG: München, 2016; pp 291–352. https://doi.org/10.3139/9781569905838.004.

[229] Singh, S.; Ramakrishna, S.; Berto, F. 3D Printing of Polymer Composites: A Short Review. *Mater. Des. Process. Commun.*, **2020**, *2* (2), e97. https://doi.org/10.1002/mdp2.97.

[230] Ziemian, C.; Sharma, M.; Ziemi, S. Anisotropic Mechanical Properties of ABS Parts Fabricated by Fused Deposition Modelling. In *Mechanical Engineering*; InTech, 2012. https://doi.org/10.5772/34233.

[231] Kozior, T.; Blachowicz, T.; Ehrmann, A. Adhesion of Three-Dimensional Printing on Textile Fabrics: Inspiration from and for Other Research Areas. *J. Eng. Fiber. Fabr.*, **2020**, *15*. https://doi.org/10.1177/1558925020910875.

[232] Sabantina, L.; Kinzel, F.; Ehrmann, A.; Finsterbusch, K. Combining 3D Printed Forms with Textile Structures - Mechanical and Geometrical Properties of Multi-Material Systems. In *2015 Global Conference on Polymer and Composite Materials (PCM2015)*; Beijing, China, 2015; Vol. 87. https://doi.org/10.1088/1757-899X/87/1/012005.

[233] Grimmelsmann, N.; Kreuziger, M.; Korger, M.; Meissner, H.; Ehrmann, A. Adhesion of 3D Printed Material on Textile Substrates. *Rapid Prototyp. J.*, **2018**, *24* (1), 166–170. https://doi.org/10.1108/RPJ-05-2016-0086.

[234] Dip, T. M.; Begum, P. D. H. A.; Hossain, M. A. Al; Uddin, M. M.; Faruque, M. O. Analysis of Physico-Mechanical Properties of Jute and Polyester Blended Yarn. *Int. J. Sci. Res. Manag.*, **2018**, *6* (09). https://doi.org/10.18535/ijsrm/v6i9.ec02.

[235] Pretreatment of Cotton Fabric https://www.htfine-chem.com/news/industry-news/pretreatment-of-cotton-fabric.html (accessed Dec 5, 2020).

[236] Kozior, T.; Döpke, C.; Grimmelsmann, N.; Juhász Junger, I.; Ehrmann, A. Influence of Fabric

Pretreatment on Adhesion of Three-Dimensional Printed Material on Textile Substrates. *Adv. Mech. Eng.*, **2018**, *10* (8), 1–8. https://doi.org/10.1177/1687814018792316.

[237] Unger, L.; Scheideler, M.; Meyer, P.; Harland, J.; Görzen, A.; Wortmann, M.; Dreyer, A.; Ehrmann, A. Increasing Adhesion of 3D Printing on Textile Fabrics by Polymer Coating. *Tekstilec*, **2018**, *61* (4), 265–271. https://doi.org/10.14502/Tekstilec2018.61.265-271.

[238] Meyer, P.; Döpke, C.; Ehrmann, A. Improving Adhesion of Three-Dimensional Printed Objects on Textile Fabrics by Polymer Coating. *J. Eng. Fiber. Fabr.*, **2019**, *14*, 1–7. https://doi.org/10.1177/1558925019895257.

[239] Grothe, T.; Sabantina, L.; Klöcker, M.; Junger, I.; Döpke, C.; Ehrmann, A. Wet Relaxation of Electrospun Nanofiber Mats. *Technologies*, **2019**, *7* (1), 23. https://doi.org/10.3390/technologies7010023.

[240] Sheron, M. N.; Igadwa, M. J.; Londiwe, N.; David, N. 3D Printing of Pla Onto Textile Fabrics. *Ann. Univ. Oradea. Fascicle Text.*, **2018**, *19* (2), 73–78.

[241] Spahiu, T.; Grimmelsmann, N.; Ehrmann, A.; Piperi, E.; Shehi, E. Effect of 3D Printing on Textile Fabric. In *1st International Conference Engineering and Entrepreneurship (ICEE)*; Tirana / Albania, 2017.

[242] Spahiu, T.; Al-Arabiyat, M.; Martens, Y.; Ehrmann, A.; Piperi, E.; Shehi, E. Adhesion of 3D Printing Polymers on Textile Fabrics for Garment Production. *IOP Conf. Ser. Mater. Sci. Eng.*, **2018**, *459* (1). https://doi.org/10.1088/1757-899X/459/1/012065.

[243] Eutionnat-Diffo, P. A.; Chen, Y.; Guan, J.; Cayla, A.; Campagne, C.; Zeng, X.; Nierstrasz, V. Optimization of Adhesion of Poly Lactic Acid 3D Printed onto Polyethylene Terephthalate Woven Fabrics through Modelling Using Textile Properties. *Rapid Prototyp. J.*, **2019**, *26* (2), 390–401. https://doi.org/10.1108/RPJ-05-2019-0138.

[244] Gurcum, B. H.; Borklu, H. R.; Sezer, K.; Eren, O. Implementing 3D Printed Structures as the Newest Textile Form. *J. Fash. Technol. Text. Eng.*, **2018**, *s4*. https://doi.org/10.4172/2329-9568.s4-019.

[245] Hudson, S. E. Printing Teddy Bears: A Technique for 3D Printing of Soft Interactive Objects. In *Conference on Human Factors in Computing Systems - Proceedings*; Association for Computing Machinery: New York, NY, USA, 2014; pp 459–468. https://doi.org/10.1145/2556288.2557338.

[246] Lipton, J. I.; Lipson, H. 3D Printing Variable Stiffness Foams Using Viscous Thread Instability. *Sci. Rep.*, **2016**, *6*, 2–7. https://doi.org/10.1038/srep29996.

[247] Sugiyama, K.; Matsuzaki, R.; Ueda, M.; Todoroki, A.; Hirano, Y. 3D Printing of Composite Sandwich Structures Using Continuous Carbon Fiber and Fiber Tension. *Compos. Part A Appl. Sci. Manuf.*, **2018**, *113*, 114–121. https://doi.org/10.1016/j.compositesa.2018.07.029.

[248] Yildirim, K.; Altun, S.; Ulcay, Y. Relationship between Yarn Properties and Process Parameters in False-Twist Textured Yarn. *J. Eng. Fiber. Fabr.*, **2009**, *4* (2), 26–32. https://doi.org/10.1177/155892500900400205.

[249] Chan, H. Sen. Creation of 3D digital printed fashion prototype with innovative surface texture | PolyU Institutional Research Archive http://ira.lib.polyu.edu.hk/handle/10397/84139 (accessed Apr 11, 2021).

[250] Wang, J. A Discussion to Presenting Texture Effects in Costume Designing in View of 3D Printing Technology. In *Proceedings of the 6th International Conference on 3D Body Scanning Technologies*; Lugano, Switzerland, 2015; pp 34–37. https://doi.org/https://doi.org/10.15221/15.034.

[251] Davis, F. 3D Printed Textiles from Textile Code: Structural Form and Material Operations. In *Proceedings of the 16th Iberoamerican Congress of Digital Graphics*; Fortaleza, Brasil, 2012; pp 327–331.

[252] Rashid, A. Additive Manufacturing Technologies. *CIRP Encycl. Prod. Eng.*, **2019**, 39–46. https://doi.org/10.1007/978-3-662-53120-4_16866.

[253] Campbell, J. R.; Whittet, C.; Britt, H. Inkjet4Tex : Creative Implications of 3D Inkjet Printing Technologies for Textiles. In *Undisciplined! Design Research Society Conference 2008*; Sheffield Hallam University: Sheffield, UK, 2009.

[254] Grimmelsmann, N.; Lutz, M.; Korger, M.; Meissner, H.; Ehrmann, A. Mechanical Properties of 3D Printed Polymers on Textile Fabrics with Interface Layer Modification. **2015**, *012005* (2015), 12005.

[255] White, J.; Foley, M.; Rowley, A. A Novel Approach to 3D-Printed Fabrics and Garments. *3D Print. Addit. Manuf.*, **2015**, *2* (3), 145–149. https://doi.org/10.1089/3dp.2015.0019.

[256] Ochola, J.; Malengier, B.; Daelemans, L.; Githaiga, J.; Langenhove, L. Van. Experimental and Numerical Analysis of the Tendon Repair Process Using Tubular Braided Fabrics. *Autex Res. J.*, **2018**, *18* (2), 121–129. https://doi.org/10.1515/aut-2017-0007.

[257] Vialva, T. The MIT scientists making 3D printed fabrics as soft as skin https://3dprintingindustry.com/news/the-mit-scientists-making-3d-printed-fabrics-as-soft-as-skin-157609/ (accessed Jun 11, 2021).

[258] Hay, Z. 3D Printed Fabric: The Most Promising Projects https://all3dp.com/2/3d-printed-fabric-most-promising-project/ (accessed Jun 11, 2021).

[259] Ham, B. Leveraging a 3D printer “defect” to create a new quasi-textile, Massachusetts Institute of Technology https://news.mit.edu/2020/defextiles-leveraging-3d-printer-defect-to-create-quasi-textiles-1020 (accessed Jun 11, 2021).

[260] Cutlip, K. Hot and Cold Comfort, Revolutionary Fabric Developed at UMD Reacts to Environmental Conditions https://today.umd.edu/articles/hot-and-cold-comfort-a77c4599-3bb4-4efd-83d2-79ac418ad018 (accessed Jun 11, 2021).

[261] Chua, J. M. NASA Eyeing “Chain Mail” Fabric for Use in Space https://www.space.com/36719-nasa-chain-mail-space-fabric.html (accessed Jun 11, 2021).

[262] Bakhtiar, S. M.; Butt, H. A.; Zeb, S.; Quddusi, D. M.; Gul, S.; Dilshad, E. 3D Printing Technologies and Their Applications in Biomedical Science. In *Omics Technologies and Bio-engineering: Towards Improving Quality of Life*; Elsevier Inc., 2018; Vol. 1, pp 167–189. https://doi.org/10.1016/B978-0-12-804659-3.00010-5.

[263] 3D Printed Fashion: How Are 3D Printers Used In The Fashion Industry? - https://www.bcn3d.com/3d-printed-fashion/ (accessed Apr 11, 2021).

[264] Richardot, A. 3D printed Fashion: Everything you need to know https://www.sculpteo.com/blog/2018/01/24/3d-printed-fashion-why-is-additive-manufacturing-interesting-for-fashion (accessed Dec 20, 2020).

[265] Kuhn, R.; Minuzzi, R. F. B. The 3D Printing's Panorama in Fashion Design. *Moda Doc. Museu, Mem. e Des.*, **2015**, *11* (1), 1–12.

[266] Kyttanen, J. Dress and Lost Luggage https://www.jannekyttanen.com/case-studies/dress-and-lost-luggage (accessed Nov 6, 2020).

[267] Reiter, R. 10 Gorgeous Dresses Created With 3D Printing https://scribol.com/art-and-design/fashion/10-gorgeous-3d-printed-dresses/6/?as=799&asv=1 (accessed Dec 20, 2020).

[268] Herpen, I. van. About Iris van Herpen https://www.irisvanherpen.com/about (accessed Nov 2, 2020).

[269] Herpen, I. van. Crystallization | Couture | Iris van Herpen https://www.irisvanherpen.com/haute-couture/crystallization (accessed Nov 2, 2020).

[270] Herpen, I. van. Haute Couture | Iris van Herpen https://www.irisvanherpen.com/haute-couture (accessed Nov 3, 2020).

[271] Brown, A. Timely enchantress: The high-tech couture of Iris van Herpen https://www.afr.com/life-and-luxury/fashion-and-style/timely-enchantress-the-high-tech-couture-of-iris-van-herpen-20200714-p55bt1 (accessed Nov 3, 2020).

[272] Chalcraft, E. Voltage 3D printed clothes by Iris van Herpen with Neri Oxman and Julia Koerner https://www.dezeen.com/2013/01/22/voltage-3d-printed-clothes-by-iris-van-herpen-with-neri-oxman-and-julia-koerne/ (accessed Nov 3, 2020).

[273] Etherington, R. Crystallization by Iris van Herpen, Daniel Widrig and .MGX by Materialise https://www.dezeen.com/2010/08/11/crystallization-by-iris-van-herpen-daniel-wright-and-mgx-by-materialise/ (accessed Dec 20, 2020).

[274] Hannah Rose Mendoza. 3D Printed Dress from Iris van Herpen Pushes Boundaries of Fashion - 3DPrint.com https://3dprint.com/201774/3d-printed-dress-iris-van-herpen/ (accessed Nov 3, 2020).

[275] Palsenbarg, V. Launch of the First Fully-functional Flexible Material in 3D Printing https://www.materialise.com/en/press-releases/launch-of-first-fully-functional-flexible-material-3d-printing (accessed Nov 2, 2020).

[276] McMahon, A. A visionary of 3-D-printed fashion | Press | Neri Oxman https://neri.media.mit.edu/press/article/a-visionary-of-3-d-printed-fashion.html (accessed Nov 3, 2020).

[277] NICCOLO CASAS http://www.niccolocasas.com/ABOUT (accessed Nov 3, 2020).

[278] Julia Koerner - JK, Salzburg| About https://www.juliakoerner.com/about-biography (accessed Nov 3, 2020).

[279] Warmann, C. Escapism by Daniel Widrig, Iris van Herpen and .MGX by Materialise https://www.dezeen.com/2011/03/04/escapism-by-daniel-widrig-iris-van-herpen-and-mgx-by-materialise/ (accessed Nov 3, 2020).

[280] Howarth, D. Iris van Herpen exhibition in Calais https://www.dezeen.com/2013/04/22/iris-van-herpen-exhibition-at-the-international-centre-for-lace-and-fashion/ (accessed Nov 3, 2020).

[281] Verlinden, J.; Doubrovski, Z.; Brink, I. van den; Verkerk, T.; Herpen, I. van. TU Delft scientists work on 3D printed dress designed by Iris van Herpen https://www.tudelft.nl/en/2018/tu-delft/tu-delft-scientists-work-on-3d-printed-dress-designed-by-iris-van-herpen/ (accessed Nov 3, 2020).

[282] ThreeASFOUR. Bahai Dress 3D printed Resin Flat Pattern pieces of Fractal interlocking weave https://threeasfour.tumblr.com/post/144768013895/threeasfour-bahai-dress-3d-printed-resin-flat (accessed Nov 6, 2020).

[283] Pearson, A. 3D Printed Fashion for New York Fashion Week, Stratasys https://www.stratasys.com/explore/blog/2016/3d-printed-dresses-new-york-fashion-week (accessed Dec 20, 2020).

[284] Harmonograph Dress & Pangolin Dress https://3dprintedart.stratasys.com/threeasfourharmonographandpangolin (accessed Dec 19, 2020).

[285] Oscillation Dress https://3dprintedart.stratasys.com/threeasfouroscillationdress (accessed Nov 6, 2020).

[286] kinematicsDress-jump - Nervous System https://n-e-r-v-o-u-s.com/projects/albums/kinematics-dress-1/content/kinematicsdress-jump/ (accessed Dec 20, 2020).

[287] Adario Strange. Inside the 3D-printed dress that may be the future of fashion https://mashable.com/2014/12/15/kinematics-3d-printed-dress/ (accessed Apr 11, 2021).

[288] Watkin, H. The Making of the Kinematics Dress by Nervous System | All3DP https://all3dp.com/kinematics-dress-nervous-system/ (accessed Apr 11, 2021).

[289] Kinematic Petals Dress - Nervous System https://n-e-r-v-o-u-s.com/projects/albums/kinematic-petals-dress/ (accessed Dec 18, 2020).

[290] Peleg, D. Forget Shopping. Soon You'll Download Your New Clothes | Danit Peleg | TED Talks - YouTube, online video https://www.youtube.com/watch?v=w1oKe8OaPbk&list=ULiQsnObyii4Q&index=991 (accessed Nov 3, 2020).

[291] Peleg, D. Liberty leading the people https://danitpeleg.com/liberty-leading-the-people-2/ (accessed Dec 20, 2020).

[292] Jessica Steinberg. At Paralympics, a 3D-printed dress for a dance with a robot https://www.timesofisrael.com/at-paralympics-a-3d-printed-dress-for-a-dance-with-a-robot/ (accessed Nov 3, 2020).

[293] Hanna Watkin. Danit Peleg Launches 3D Printed Jacket Costing $1,500 https://all3dp.com/danit-peleg-3d-printed-jacket/ (accessed Nov 4, 2020).

[294] Erin Winick. Want your own 3D printed clothes? Danit Peleg wants to make them for you https://medium.com/. Available at: https://medium.com/s/technology-shaping-the-fashion-industry/want-your-own-3d-printed-clothes-danit-peleg-wants-to-make-them-for-you-b80addc84934 (accessed Nov 3, 2020).

[295] Peleg, D. Paralympics Dress https://danitpeleg.com/paralympics-dress/ (accessed Nov 3, 2020).

[296] Daviy, J. Collection Projects: Digital 3D-Printed Clothes, Accessories, Jewelry https://juliadaviy.com/liberation-collection/ (accessed Jun 3, 2021).

[297] Fibre2Fashion. Pollution by Textile Industry - Pollutants of Water, Air, Land, Environmental Pollution By Textile Industry. *Fibre2Fashion*. May 2012.

[298] Morgen. Designer Julia Daviy Stuns at New York Fashion Week with Functional 3D Printed Fashion Collection - Perfect 3D Printing Filament https://www.morgen-filament.de/designer-julia-daviy-stuns-at-new-york-fashion-week-with-functional-3d-printed-fashion-collection/ (accessed Nov 5, 2020).

[299] Daivy, J. New Clean Innovative Luxury https://juliadaviy.com/press-kit-3d-printed-clothing-collection-printed-on-large-3d-printers-thats-the-beginning-for-use-of-3d-printing-in-fashion-industry (accessed Nov 5, 2020).

[300] Sharma, R. Lady Gaga Goes Gaga Over 3D Printing https://www.forbes.com/sites/rakeshsharma/2013/12/06/lady-gaga-goes-gaga-over-3d-printing/?sh=1819616f1680 (accessed Dec 19, 2020).

[301] Adlughmin. The "Synapse Dress": Intuitive 3D Printed Wearable Body Response Dress by Anouk Wipprecht - 3DPrint.Com. *The Voice of 3D Printing / Additive Manufacturing*. September 2014.

[302] Farahi, B. Caress of the Gaze: A Gaze Actuated 3D Printed Body Architecture. In *ACADIA 2016: Posthuman Frontiers: Data, Designers, and Cognitive Machines - Proceedings of the 36th Annual Conference of the Association for Computer Aided Design in Architecture*; 2016; pp 352–361.

[303] Daivy, J. New Clean Innovative Luxury https://juliadaviy.com/liberation-collection/ (accessed Nov 7, 2020).

[304] Taylor, A.; Unver, E. 3D Printing- Media Hype or Manufacturing Reality: Textiles Surface Fashion Product Architecture. In *Textiles Society Lecture*; Textile Centre of Excellence, Huddersfield UK, 2014.

[305] Schouwer, F. De. Mind-blowing 3D printed fashion | 3D Printing Blog | i.materialise https://i.materialise.com/blog/en/mind-blowing-3d-printed-fashion/ (accessed Nov 2, 2020).

[306] Melkebeek, J. Van. Iris van Herpen's new 3D printed Escapism couture collection for .MGX | 3D Printing Blog | i.materialise https://i.materialise.com/blog/en/iris-van-herpens-new-3d-printed-escapism-couture-collection-for-mgx/ (accessed Nov 2, 2020).

[307] Scaturro, S.; Museum, C.; Scaturro, S.; Ground, B. Re-Imagining Embellishment : The Conservation of Iris van Herpen ' s Radically Engineered Surfaces. In *North American Textile Conservation Conference*; Mexico City, Mexico, 2017.

[308] Borrelli-Persson, L. Iris van Herpen Spring 2012 Couture Collection https://www.vogue.com/fashion-shows/spring-2012-couture/iris-van-herpen (accessed Nov 2, 2020).

[309] Oxman, N. Anthozoa: Cape & Skirt, 3-D Printed Dress in collaboration with Iris Van Herpen https://www.media.mit.edu/ (accessed Nov 2, 2020).

[310] Herpen, Iris Van; Oxman, N. Anthozoa 3D Cape and Skirt

https://artsandculture.google.com/culturalinstitute/beta/asset/anthozoa-3d-cape-and-skirt-iris-van-herpen/4QFs8PrZkzpJpg (accessed Nov 2, 2020).

[311] Iris van Herpen's Wilderness Embodied Collection is Unveiled in Paris and Includes Her First Hybrid 3D Printed Dress https://www.materialise.com/en/press-releases/iris-van-herpens-wilderness-embodied-collection-unveiled-paris-and-includes-her (accessed Nov 2, 2020).

[312] BIOPIRACY DRESS https://www.juliakoerner.com/biopiracy (accessed Nov 2, 2021).

[313] Casas, Niccolo; Herpen, I. Van. MAGNETIC MOTION - niccolocasas http://www.niccolocasas.com/MAGNETIC-MOTION (accessed Nov 2, 2020).

[314] Casas, Niccolo; Herpen, I. Van. HACKING INFINITY - niccolocasas http://www.niccolocasas.com/HACKING-INFINITY (accessed Nov 3, 2020).

[315] Palsenbarg, V. The Dream-Like "Lucid" Collection by Iris van Herpen https://www.materialise.com/en/blog/dream-like-lucid-collection-by-iris-van-herpen (accessed Nov 3, 2020).

[316] Boissonneault, T. Iris van Herpen's FW collection Lucid for fall 2016 features dreamlike 3D printed dresses | 3D Printer News https://www.3ders.org/articles/20160309-iris-van-herpens-fw-collection-lucid-features-dreamlike-3d-printed-dresses.html (accessed Nov 3, 2020).

[317] Valdivieso, C. Designer Julia Daviy on disrupting and bringing sustainability to the fashion industry https://www.3dnatives.com/en/julia-daviy-280520194/ (accessed Nov 5, 2020).

[318] Armstrong, K. 3D printed dress debuts at New York Fashion Week https://3dprintingindustry.com/news/3d-printed-dress-debuts-new-york-fashion-week-95736/ (accessed Nov 6, 2020).

[319] Kinematics Dress 1 https://n-e-r-v-o-u-s.com/projects/albums/kinematics-dress-1/ (accessed Dec 2, 2020).

[320] XYZ Workshop & Ultimaker launch 3D printable Fashion Suite https://www.3ders.org/articles/20140819-xyz-workshop-ultimaker-launch-3d-printable-fashion-suite.html (accessed Dec 18, 2020).

[321] 3D Printed Textiles - LOOM Dress https://www.mariale.design/loom (accessed Dec 18, 2020).

[322] Delaney, A. Melinda Looi, and Samuel Canning Present 'Gems of the Ocean', 3D-Printed Collection at Meckler Media's 3D Print Week New York https://www.materialise.com/en/blog/materialise-melinda-looi-and-samuel-canning-present-gems-of-ocean-3d-printed-collection-at (accessed Dec 18, 2020).

[323] O'Connell, J. 3D Printed Dress: 10 Awesome Projects. *All3DP*. 18/12/2020 September 2020.

[324] MakerBot. Francis Bitonti's New Skins https://www.makerbot.com/stories/design/makerbot-explorers-francis-bitontis-new-skins/ (accessed Dec 19, 2020).

[325] MakerBot. Francis Bitonti on the Bristle Dress https://www.makerbot.com/stories/design/makerbot-stories-francis-bitonti-bristle-dress/ (accessed Dec 19, 2020).

[326] Hurst, N. Dita Von Teese Flaunts Fibonacci-Inspired, 3-D Printed Gown | WIRED

https://www.wired.com/2013/03/dita-von-teese-3-d-printed-gown/ (accessed Dec 19, 2020).

[327] Williamson, C. Dita's Gown: A 3D Printed Dress https://design-milk.com/ditas-gown-a-3d-printed-dress/ (accessed Dec 19, 2020).

[328] Scott, D. Victoria's Secret Snow Queen 3D Print: Interview with Bradley Rothenberg - Shapeways Blog https://www.shapeways.com/blog/archives/2342-victorias-secret-snow-queen-3d-print-interview-with-bradley-rothenberg.html (accessed Dec 19, 2020).

[329] Dhuru, R. Marina Hoermanseder and Julia Koerner's Smock Corset: How 3D Printing Is (Literally) Shaping Fashion Today https://www.materialise.com/en/blog/marina-hoermanseder-and-julia-koerners-smock-corset-how-3d-printing-literally-shaping-fashion (accessed Dec 19, 2020).

[330] The Sporophyte Collection https://3dprintedart.stratasys.com/juliakoernersporophyte (accessed Dec 19, 2021).

[331] Park, R. 3D Printed Dress of Pia Hinze Features in Muuse x Vogue Awards - 3D Printing Industry https://3dprintingindustry.com/news/3d-printed-dress-of-pia-hinze-features-in-muuse-x-vogue-awards-15528/ (accessed Dec 19, 2020).

[332] Oxman, N. Otaared, Mercury's Wanderer https://neri.media.mit.edu/projects/details/otaared.html (accessed Dec 19, 2020).

[333] Simon. This 3d printed robotic Spider dress is perfect for somebody who needs "space" | 3D Printer News https://www.3ders.org/articles/20141223-this-3d-printed-robotic-spider-dress-is-perfect-for-somebody-who-needs-space.html (accessed Dec 19, 2020).

[334] Molitch-Hou, M. Maartje Dijkstra's 3D Printed Ensemble - 3D Printing Industry https://3dprintingindustry.com/news/maartje-dijkstras-3d-printed-ensemble-36189/ (accessed Dec 19, 2020).

[335] SMOKE DRESS - niccolocasas http://www.niccolocasas.com/SMOKE-DRESS (accessed Dec 19, 2020).

[336] Swennen, G. R. J.; Pottel, L.; Haers, P. E. Custom-Made 3D-Printed Face Masks in Case of Pandemic Crisis Situations with a Lack of Commercially Available FFP2/3 Masks. *Int. J. Oral Maxillofac. Surg.*, **2020**, *49* (5), 673–677. https://doi.org/10.1016/j.ijom.2020.03.015.

[337] Lim, H.; Cassidy, T. 3D Printing Technology Revolution in Future Sustainable Fashion. In *2014 International Textiles & Costume Culture Congress(ITCCC): Sustainability in Textiles and Fashion*; Jeonju, South Korea, 2014; pp 1–4.

[338] Cheng-Yu, H.; Ahmed Abro, Z.; Yi-Fan, Z.; Ahmed Lakho, R. An FBG-Based Smart Wearable Ring Fabricated Using FDM for Monitoring Body Joint Motion. *J. Ind. Text.*, **2019**, 1–14. https://doi.org/10.1177/1528083719870204.

[339] MacDonald, E.; Wicker, R. Multiprocess 3D Printing for Increasing Component Functionality. *Science (80-.).*, **2016**, *353* (6307). https://doi.org/10.1126/science.aaf2093.

[340] Hamzah, H. H.; Shafiee, S. A.; Abdalla, A.; Patel, B. A. 3D Printable Conductive Materials for the Fabrication of Electrochemical Sensors: A Mini Review. *Electrochem. commun.*, **2018**, *96*, 27–31.

[341] Farahani, R. D.; Dalir, H.; Le Borgne, V.; Gautier, L. A.; El Khakani, M. A.; Lévesque, M.; Therriault, D. Direct-Write Fabrication of Freestanding Nanocomposite Strain Sensors. *Nanotechnology*,

2012, *23* (8), 85502. https://doi.org/10.1088/0957-4484/23/8/085502.

[342] Farahani, R. D.; Dubé, M.; Therriault, D. Three-dimensional Printing of Multifunctional Nanocomposites: Manufacturing Techniques and Applications. *Adv. Mater.*, **2016**, *28* (28), 5794–5821. https://doi.org/https://doi.org/10.1002/adma.201506215.

[343] Nathan-Walleser, T.; Lazar, I.; Fabritius, M.; Tölle, F. J.; Xia, Q.; Bruchmann, B.; Venkataraman, S. S.; Schwab, M. G.; Mülhaupt, R. 3D Micro-Extrusion of Graphene-based Active Electrodes: Towards High-Rate AC Line Filtering Performance Electrochemical Capacitors. *Adv. Funct. Mater.*, **2014**, *24* (29), 4706–4716. https://doi.org/https://doi.org/10.1002/adfm.201304151.

[344] Zhao, C.; Wang, C.; Gorkin Iii, R.; Beirne, S.; Shu, K.; Wallace, G. G. Three Dimensional (3D) Printed Electrodes for Interdigitated Supercapacitors. *Electrochem. commun.*, **2014**, *41*, 20–23. https://doi.org/https://doi.org/10.1016/j.elecom.2014.01.013.

[345] Ambrosi, A.; Moo, J. G. S.; Pumera, M. Helical 3D-Printed Metal Electrodes as Custom-Shaped 3D Platform for Electrochemical Devices. *Adv. Funct. Mater.*, **2016**, *26* (5), 698–703. https://doi.org/10.1002/adfm.201503902.

[346] Guo, S.; Yang, X.; Heuzey, M.-C.; Therriault, D. 3D Printing of a Multifunctional Nanocomposite Helical Liquid Sensor. *Nanoscale*, **2015**, *7* (15), 6451–6456. https://doi.org/https://doi.org/10.1039/C5NR00278H.

[347] Distler, T.; Boccaccini, A. R. 3D Printing of Electrically Conductive Hydrogels for Tissue Engineering and Biosensors–A Review. *Acta Biomater.*, **2020**, *101*, 1–13. https://doi.org/https://doi.org/10.1016/j.actbio.2019.08.044.

[348] Chee, W. K.; Lim, H. N.; Huang, N. M.; Harrison, I. Nanocomposites of Graphene/Polymers: A Review. *Rsc Adv.*, **2015**, *5* (83), 68014–68051. https://doi.org/https://doi.org/10.1039/C5RA07989F.

[349] Leigh, S. J.; Purssell, C. P.; Bowen, J.; Hutchins, D. A.; Covington, J. A.; Billson, D. R. A Miniature Flow Sensor Fabricated by Micro-Stereolithography Employing a Magnetite/Acrylic Nanocomposite Resin. *Sensors Actuators A Phys.*, **2011**, *168* (1), 66–71. https://doi.org/https://doi.org/10.1016/j.sna.2011.03.058.

[350] Leigh, S. J.; Bradley, R. J.; Purssell, C. P.; Billson, D. R.; Hutchins, D. A. A Simple, Low-Cost Conductive Composite Material for 3D Printing of Electronic Sensors. *PLoS One*, **2012**, *7* (11), 49365. https://doi.org/10.1371/journal.pone.0049365.

[351] Adams, J. J.; Duoss, E. B.; Malkowski, T. F.; Motala, M. J.; Ahn, B. Y.; Nuzzo, R. G.; Bernhard, J. T.; Lewis, J. A. Conformal Printing of Electrically Small Antennas on Three-dimensional Surfaces. *Adv. Mater.*, **2011**, *23* (11), 1335–1340. https://doi.org/https://doi.org/10.1002/adma.201003734.

[352] Grimmelsmann, N.; Martens, Y.; Schäl, P.; Meissner, H.; Ehrmann, A. Mechanical and Electrical Contacting of Electronic Components on Textiles by 3D Printing. *Procedia Technol.*, **2016**, *26*, 66–71. https://doi.org/10.1016/j.protcy.2016.08.010.

[353] Aissa, B.; Therriault, D.; Farahani, R. D.; Lebel, L. L.; El Khakani, M. A. Electrical Transport Properties of Single Wall Carbon Nanotube/Polyurethane Composite Based Field Effect Transistors Fabricated by UV-Assisted Direct-Writing Technology. *Nanotechnology*, **2012**, *23* (11), 115705.

[354] Farahani, R. D.; Chizari, K.; Therriault, D. Three-Dimensional Printing of Freeform Helical Microstructures: A Review. *Nanoscale*, **2014**, *6* (18), 10470–10485. https://doi.org/https://doi.org/10.1039/C4NR02041C.

[355] Lebel, L. L.; Aissa, B.; Khakani, M. A. El; Therriault, D. Ultraviolet-assisted Direct-write Fabrication of Carbon Nanotube/Polymer Nanocomposite Microcoils. *Adv. Mater.*, **2010**, *22* (5), 592–596. https://doi.org/https://doi.org/10.1002/adma.200902192.

[356] Yin, X.-Y.; Zhang, Y.; Cai, X.; Guo, Q.; Yang, J.; Wang, Z. L. 3D Printing of Ionic Conductors for High-Sensitivity Wearable Sensors. *Mater. Horizons*, **2019**, *6* (4), 767–780. https://doi.org/https://doi.org/10.1039/C8MH01398E.

[357] Abdelkader, A. M.; Karim, N.; Vallés, C.; Afroj, S.; Novoselov, K. S.; Yeates, S. G. Ultraflexible and Robust Graphene Supercapacitors Printed on Textiles for Wearable Electronics Applications. *2D Mater.*, **2017**, *4* (3). https://doi.org/10.1088/2053-1583/aa7d71.

[358] Frutiger, A.; Muth, J. T.; Vogt, D. M.; Mengüç, Y.; Campo, A.; Valentine, A. D.; Walsh, C. J.; Lewis, J. A. Capacitive Soft Strain Sensors via Multicore–Shell Fiber Printing. *Adv. Mater.*, **2015**, *27* (15), 2440–2446. https://doi.org/https://doi.org/10.1002/adma.201500072.

[359] Khosravani, M. R.; Reinicke, T. 3D-Printed Sensors: Current Progress and Future Challenges. *Sensors Actuators A Phys.*, **2020**, *305*, 111916. https://doi.org/https://doi.org/10.1016/j.sna.2020.111916.

[360] Ni, Y.; Ji, R.; Long, K.; Bu, T.; Chen, K.; Zhuang, S. A Review of 3D-Printed Sensors. *Appl. Spectrosc. Rev.*, **2017**, *52* (7), 623–652. https://doi.org/https://doi.org/10.1080/05704928.2017.1287082.

[361] Pang, C.; Lee, C.; Suh, K. Recent Advances in Flexible Sensors for Wearable and Implantable Devices. *J. Appl. Polym. Sci.*, **2013**, *130* (3), 1429–1441. https://doi.org/https://doi.org/10.1002/app.39461.

[362] He, H.; Akbari, M.; Sydänheimo, L.; Ukkonen, L.; Virkki, J. 3D-Printed Graphene Antennas and Interconnections for Textile RFID Tags: Fabrication and Reliability towards Humidity. *Int. J. Antennas Propag.*, **2017**, *2017*. https://doi.org/https://doi.org/10.1155/2017/1386017.

[363] He, H.; Chen, X.; Ukkonen, L.; Virkki, J. Textile-Integrated Three-Dimensional Printed and Embroidered Structures for Wearable Wireless Platforms. *Text. Res. J.*, **2019**, *89* (4), 541–550. https://doi.org/10.1177/0040517517750649.

[364] Rivera, M. L.; Moukperian, M.; Ashbrook, D.; Mankoff, J.; Hudson, S. E. Stretching the Bounds of 3D Printing with Embedded Textiles. In *Conference on Human Factors in Computing Systems - Proceedings*; Association for Computing Machinery: New York, NY, USA, 2017; Vol. 2017-May, pp 497–508. https://doi.org/10.1145/3025453.3025460.

[365] Foncu-Berk, G. 3D Printing of Conductive and Phosphorescent Filaments onto Textile. In *ITAA Proceedings*; Las Vegas, Nevada, 2019; pp 3–5.

[366] Asaka, K.; Okuzaki, H. *Soft Actuators: Materials, Modeling, Applications, and Future Perspectives*; Springer Japan, 2019. https://doi.org/10.1007/978-4-431-54767-9.

[367] Zolfagharian, A.; Kouzani, A. Z.; Khoo, S. Y.; Moghadam, A. A. A.; Gibson, I.; Kaynak, A. Evolution of 3D Printed Soft Actuators. *Sensors Actuators, A Phys.*, **2016**, *250*, 258–272. https://doi.org/10.1016/j.sna.2016.09.028.

[368] ISO. About us https://www.iso.org/about-us.html (accessed Dec 5, 2020).

[369] Razieh, A.; Sanatgar, H.; Campagne, C.; Nierstrasz, V. Investigation of the Adhesion Properties of Direct 3D Printing of Polymers. *Appl. Surf. Sci.*, **2017**, *403* (2017), 551–563. https://doi.org/10.1016/j.apsusc.2017.01.112.

[370] Fafenrot, S.; Grimmelsmann, N.; Wortmann, M.; Ehrmann, A. Three-Dimensional (3D) Printing of Polymer-Metal Hybrid Materials by Fused Deposition Modeling. *Materials (Basel).*, **2017**, *10* (10). https://doi.org/10.3390/ma10101199.

[371] ASTM International. About Us https://www.astm.org/ (accessed Dec 5, 2020).

[372] ISO 6133:2015 Rubber and plastics — Analysis of multi-peak traces obtained in determinations of tear strength and adhesion strength https://www.iso.org/standard/65921.html (accessed Nov 5, 2020).

[373] ISO 13934-1:2013, Textiles — Tensile properties of fabrics — Part 1: Determination of maximum force and elongation at maximum force using the strip method https://www.iso.org/standard/60676.html (accessed Nov 4, 2020).

[374] ISO 12947-2:2016 Textiles — Determination of the abrasion resistance of fabrics by the Martindale method — Part 2: Determination of specimen breakdown https://www.iso.org/standard/61058.html (accessed Nov 4, 2020).

[375] ISO 15797:2017 Textiles — Industrial washing and finishing procedures for testing of workwear https://www.iso.org/standard/65152.html (accessed Nov 4, 2020).

[376] ISO 2411:2017 Rubber- or plastics-coated fabrics — Determination of coating adhesion https://www.iso.org/standard/70220.html (accessed Nov 5, 2020).

[377] ISO 11339:2010 Adhesives — T-peel test for flexible-to-flexible bonded assemblies https://www.iso.org/standard/52890.html (accessed Nov 5, 2020).

[378] ISO 527-3:1995 Plastics — Determination of tensile properties — Part 3: Test conditions for films and sheets https://www.iso.org/standard/4594.html (accessed Nov 3, 2020).

[379] ISO 6330:2012, Textiles — Domestic washing and drying procedures for textile testing https://www.iso.org/standard/43044.html (accessed Nov 4, 2020).

[380] ISO 5084:1996, Textiles — Determination of thickness of textiles and textile products https://www.iso.org/standard/23348.html (accessed Nov 5, 2020).

[381] ISO 604:2002 Plastics — Determination of compressive properties https://www.iso.org/standard/31261.html (accessed Nov 3, 2020).

[382] ISO 527-1:2019 Plastics — Determination of tensile properties — Part 1: General principles https://www.iso.org/standard/75824.html (accessed Nov 5, 2020).

[383] ASTM D575 - 91(2018) Standard Test Methods for Rubber Properties in Compression http://www.astm.org/cgi-bin/resolver.cgi?D575-91(2018) (accessed Nov 6, 2020).

[384] ASTM D1238 - 20 Standard Test Method for Melt Flow Rates of Thermoplastics by Extrusion Plastometer http://www.astm.org/cgi-bin/resolver.cgi?D1238-20 (accessed Nov 6, 2020).

[385] ASTM D5034 - 09 Standard Test Method for Breaking Strength and Elongation of Textile Fabrics

(Grab Test) http://www.astm.org/cgi-bin/resolver.cgi?D5034-09 (accessed Nov 6, 2020).

[386] ASTM D5170 - 98(2015) Standard Test Method for Peel Strength (“T” Method) of Hook and Loop Touch Fasteners http://www.astm.org/cgi-bin/resolver.cgi?D5170-98(2015) (accessed Nov 6, 2020).

[387] ASTM D570 - 98(2018) Standard Test Method for Water Absorption of Plastics http://www.astm.org/cgi-bin/resolver.cgi?D570-98(2018) (accessed Nov 6, 2020).

[388] ASTM D3763 - 18 Standard Test Method for High Speed Puncture Properties of Plastics Using Load and Displacement Sensors http://www.astm.org/cgi-bin/resolver.cgi?D3763-18 (accessed Nov 6, 2020).

[389] ASTM D6110 - 10 Standard Test Method for Determining the Charpy Impact Resistance of Notched Specimens of Plastics http://www.astm.org/cgi-bin/resolver.cgi?D6110-10 (accessed Nov 6, 2020).

[390] ASTM D790 - 17 Standard Test Methods for Flexural Properties of Unreinforced and Reinforced Plastics and Electrical Insulating Materials http://www.astm.org/cgi-bin/resolver.cgi?D790-17 (accessed Nov 6, 2020).

[391] Mohamed, O. A.; Masood, S. H.; Bhowmik, J. L. Optimization of Fused Deposition Modeling Process Parameters: A Review of Current Research and Future Prospects. *Adv. Manuf.*, **2015**, *3* (1), 42–53. https://doi.org/10.1007/s40436-014-0097-7.

[392] Lanzotti, A.; Martorelli, M.; Staiano, G. Understanding Process Parameter Effects of Reprap Open-Source Three-Dimensional Printers through a Design of Experiments Approach. *J. Manuf. Sci. Eng. Trans. ASME*, **2015**, *137* (1). https://doi.org/10.1115/1.4029045.

[393] Sood, A. K.; Ohdar, R. K.; Mahapatra, S. S. Parametric Appraisal of Mechanical Property of Fused Deposition Modelling Processed Parts. *Mater. Des.*, **2010**, *31* (1), 287–295. https://doi.org/10.1016/j.matdes.2009.06.016.

[394] Qureshi, A. J.; Mahmood, S.; Wong, W. L. E.; Talamona, D. Design for Scalability and Strength Optimisation for Components Created through Fdm Process. In *20th International Conference on Engineering Design (ICED 15)*; Milan, Italy, 2015; Vol. 6.

[395] Geng, P.; Zhao, J.; Wu, W.; Ye, W.; Wang, Y.; Wang, S.; Zhang, S. Effects of Extrusion Speed and Printing Speed on the 3D Printing Stability of Extruded PEEK Filament. *J. Manuf. Process.*, **2019**, *37*, 266–273. https://doi.org/10.1016/j.jmapro.2018.11.023.

[396] Caulfield, B.; McHugh, P. E.; Lohfeld, S. Dependence of Mechanical Properties of Polyamide Components on Build Parameters in the SLS Process. *J. Mater. Process. Technol.*, **2007**, *182* (1–3), 477–488. https://doi.org/10.1016/j.jmatprotec.2006.09.007.

[397] Stampfl, J.; Baudis, S.; Heller, C.; Liska, R.; Neumeister, A.; Kling, R.; Ostendorf, A.; Spitzbart, M. Photopolymers with Tunable Mechanical Properties Processed by Laser-Based High-Resolution Stereolithography. *J. Micromechanics Microengineering*, **2008**, *18* (12). https://doi.org/10.1088/0960-1317/18/12/125014.

[398] Sood, A. K.; Ohdar, R. K.; Mahapatra, S. S. Improving Dimensional Accuracy of Fused Deposition Modelling Processed Part Using Grey Taguchi Method. *Mater. Des.*, **2009**, *30* (10), 4243–4252. https://doi.org/10.1016/j.matdes.2009.04.030.

[399] Nancharaiah, T.; Raju, D. R.; Raju, V. R. An Experimental Investigation on Surface Quality and Dimensional Accuracy of FDM Components. *Int. J. Emerg. Technol.*, **2010**, *1* (2), 106–111.

[400] Zhang, J.; Peng, A. Process-Parameter Optimization for Fused Deposition Modeling Based on Taguchi Method. In *Advanced Materials Research*; 2012; Vol. 538–541, pp 444–447. https://doi.org/10.4028/www.scientific.net/AMR.538-541.444.

[401] Sahu, R. K.; Mahapatra, S. S.; Sood, A. K. A Study on Dimensional Accuracy of Fused Deposition Modeling (FDM) Processed Parts Using Fuzzy Logic. *J. Manuf. Sci. Prod.*, **2014**, *13* (3), 183–197. https://doi.org/10.1515/jmsp-2013-0010.

[402] Anitha, R.; Arunachalam, S.; Radhakrishnan, P. Critical Parameters Influencing the Quality of Prototypes in Fused Deposition Modelling. In *Journal of Materials Processing Technology*; Elsevier, 2001; Vol. 118, pp 385–388. https://doi.org/10.1016/S0924-0136(01)00980-3.

[403] Thrimurthulu, K.; Pandey, P. M.; Reddy, N. V. Optimum Part Deposition Orientation in Fused Deposition Modeling. *Int. J. Mach. Tools Manuf.*, **2004**, *44* (6), 585–594. https://doi.org/10.1016/j.ijmachtools.2003.12.004.

[404] Horvath, D.; Noorani, R.; Mendelson, M. Improvement of Surface Roughness on ABS 400 Polymer Using Design of Experiments (DOE). *Mater. Sci. Forum*, **2007**, *561–565*, 2389–2392. https://doi.org/10.4028/www.scientific.net/msf.561-565.2389.

[405] Ahn, S. H.; Montero, M.; Odell, D.; Roundy, S.; Wright, P. K. *Anisotropic Material Properties of Fused Deposition Modeling ABS*; 2002; Vol. 8. https://doi.org/10.1108/13552540210441166.

[406] Ang, K. C.; Leong, K. F.; Chua, C. K.; Chandrasekaran, M. Investigation of the Mechanical Properties and Porosity Relationships in Fused Deposition Modelling-Fabricated Porous Structures. *Rapid Prototyp. J.*, **2006**, *12* (2), 100–105. https://doi.org/10.1108/13552540610652447.

[407] Percoco, G.; Lavecchia, F.; Galantucci, L. M. Compressive Properties of FDM Rapid Prototypes Treated with a Low Cost Chemical Finishing. *Res. J. Appl. Sci. Eng. Technol.*, **2012**, *4* (19), 3838–3842.

[408] Rayegani, F.; Onwubolu, G. C. Fused Deposition Modelling (Fdm) Process Parameter Prediction and Optimization Using Group Method for Data Handling (Gmdh) and Differential Evolution (De). *Int. J. Adv. Manuf. Technol.*, **2014**, *73* (1–4), 509–519. https://doi.org/10.1007/s00170-014-5835-2.

[409] Nancharaiah, T. Optimization of Process Parameters in FDM Process Using Design of Experiments. *Int. J. Emerg. Technol. 2(1)*, **2011**, *2* (1), 100–102.

[410] Pavan Kumar, G.; Regalla, S. P. Optimization of Support Material and Build Time in Fused Deposition Modeling (FDM). In *Applied Mechanics and Materials*; 2012; Vol. 110–116, pp 2245–2251. https://doi.org/10.4028/www.scientific.net/AMM.110-116.2245.

[411] Lee, B. H.; Abdullah, J.; Khan, Z. A. Optimization of Rapid Prototyping Parameters for Production of Flexible ABS Object. *J. Mater. Process. Technol.*, **2005**, *169* (1), 54–61. https://doi.org/10.1016/j.jmatprotec.2005.02.259.

[412] Laeng, J.; Khan, Z. A.; Khu, S. Y. Optimizing Flexible Behaviour of Bow Prototype Using Taguchi Approach. *J. Appl. Sci.*, **2006**, *6* (3), 622–630. https://doi.org/10.3923/jas.2006.622.630.

[413] Zhang, Y.; Chou, K. A Parametric Study of Part Distortions in Fused Deposition Modelling Using Three-Dimensional Finite Element Analysis. *Proc. Inst. Mech. Eng. Part B J. Eng. Manuf.*, **2008**, *222* (8), 959–968. https://doi.org/10.1243/09544054JEM990.

[414] Baich, L.; Manogharan, G.; Marie, H. Study of Infill Print Design on Production Cost-Time of 3D Printed ABS Parts. *Int. J. Rapid Manuf.*, **2015**, *5* (3/4), 308. https://doi.org/10.1504/ijrapidm.2015.074809.

[415] Hossain, M. S.; Ramos, J.; Espalin, D.; Perez, M.; Wicker, R. Improving Tensile Mechanical Properties of FDM-Manufactured Specimens via Modifying Build Parameters. *24th Int. SFF Symp. - An Addit. Manuf. Conf. SFF 2013*, **2013**, 380–392.

[416] Masood, S. H.; Mau, K.; Song, W. Q. Tensile Properties of Processed FDM Polycarbonate Material. In *Materials Science Forum*; Trans Tech Publications Ltd, 2010; Vol. 654–656, pp 2556–2559. https://doi.org/10.4028/www.scientific.net/MSF.654-656.2556.

[417] Akande, S. O.; Dalgarno, K. W.; Munguia, J. Low-Cost QA Benchmark for Fused Filament Fabrication. *3D Print. Addit. Manuf.*, **2015**, *2* (2), 78–84. https://doi.org/10.1089/3dp.2015.0012.

[418] Rankouhi, B.; Javadpour, S.; Delfanian, F.; Letcher, T. Failure Analysis and Mechanical Characterization of 3D Printed ABS With Respect to Layer Thickness and Orientation. *J. Fail. Anal. Prev.*, **2016**, *16* (3), 467–481. https://doi.org/10.1007/s11668-016-0113-2.

[419] Lanzotti, A.; Grasso, M.; Staiano, G.; Martorelli, M. The Impact of Process Parameters on Mechanical Properties of Parts Fabricated in PLA with an Open-Source 3-D Printer. *Rapid Prototyp. J.*, **2015**, *21* (5), 604–617. https://doi.org/10.1108/RPJ-09-2014-0135.

[420] Mikkonen, J.; Myllymäki, R.; Kivioja, S. Printed Material and Fabric. In *Nordic Design Research Conference 2013*; Nordic Design Research: Copenhagen-Malmö, 2013; pp 313–321.

[421] Khatwani, J.; Srivastava, V. Effect of Process Parameters on Mechanical Properties of Solidified PLA Parts Fabricated by 3D Printing Process. In *3D Printing and Additive Manufacturing Technologies*; Springer Singapore, 2018; pp 95–104. https://doi.org/10.1007/978-981-13-0305-0_9.

[422] Kuang, X.; Zhao, Z.; Chen, K.; Fang, D.; Kang, G.; Qi, H. J. High-Speed 3D Printing of High-Performance Thermosetting Polymers via Two-Stage Curing. *Macromol. Rapid Commun.*, **2018**, *39* (7), 1700809. https://doi.org/10.1002/marc.201700809.

[423] How to Make Resin 3D Printing 8x Faster and 9x More Precise | Zortrax https://zortrax.com/blog/resin-3d-printing-faster-and-more-precise/ (accessed Dec 16, 2020).

[424] Carpenter, S. 3D Printing Speed : How long does 3d Printing take https://www.sculpteo.com/en/glossary/3d-printing-speed-definition/ (accessed Dec 11, 2020).

[425] Jain, P. K.; Pandey, P. M.; Rao, P. V. M. Effect of Delay Time on Part Strength in Selective Laser Sintering. *Int. J. Adv. Manuf. Technol.*, **2009**, *43* (1–2), 117–126. https://doi.org/10.1007/s00170-008-1682-3.

[426] Costa, S. F.; Duarte, F. M.; Covas, J. A. Estimation of Filament Temperature and Adhesion Development in Fused Deposition Techniques. *J. Mater. Process. Technol.*, **2017**, *245*, 167–179. https://doi.org/10.1016/j.jmatprotec.2017.02.026.

[427] Sun, Q.; Rizvi, G. M.; Bellehumeur, C. T.; Gu, P. Effect of Processing Conditions on the Bonding Quality of FDM Polymer Filaments. *Rapid Prototyp. J.*, **2008**, *14* (2), 72–80. https://doi.org/10.1108/13552540810862028.

[428] Pavlic, T.; Cikic, A.; Golubic, S. Analysis of the Influence of 3D Printing on Hardness of Parts. *Teh. Vjesn. - Tech. Gaz.*, **2016**, *23* (3), 843–848.

[429] Faruk, O.; Bledzki, A. K.; Fink, H. P.; Sain, M. Biocomposites Reinforced with Natural Fibers: 2000-2010. *Prog. Polym. Sci.*, **2012**, *37* (11), 1552–1596. https://doi.org/10.1016/j.progpolymsci.2012.04.003.

[430] Malengier, B.; Hertleer, C.; Langenhove, V.; Cardon, L. 3D Printing on Textiles: Testing of Adhesion. In *ITMC2017-International Conference on Intelligent Textiles and Mass Customisation*; Gent, 2017. https://doi.org/10.4172/2329-9568.s4-013.

[431] Hashemi Sanatgar, R.; Campagne, C.; Nierstrasz, V. Investigation of the Adhesion Properties of Direct 3D Printing of Polymers and Nanocomposites on Textiles: Effect of FDM Printing Process Parameters. *Appl. Surf. Sci.*, **2017**, *403*, 551–563. https://doi.org/10.1016/j.apsusc.2017.01.112.

[432] Tello, J. A.; Zapata, M.; Paillacho, D. Advances in Additive Manufacturing, Modeling Systems and 3D Prototyping. In *Proceedings of the AHFE 2019 International Conference on Additive Manufacturing, Modeling Systems and 3D Prototyping*; 2020; Vol. 975, pp 108–118. https://doi.org/10.1007/978-3-030-20216-3.

[433] Chatterjee, K.; Ghosh, T. K. 3D Printing of Textiles: Potential Roadmap to Printing with Fibers. *Adv. Mater.*, **2020**, *32* (4), 1–24. https://doi.org/10.1002/adma.201902086.

[434] Awaja, F.; Gilbert, M.; Kelly, G.; Fox, B.; Pigram, P. J. Adhesion of Polymers. *Prog. Polym. Sci.*, **2009**, *34* (9), 948–968. https://doi.org/10.1016/j.progpolymsci.2009.04.007.

[435] Crookston, J. J.; Long, A. C.; Bingham, G. A.; Hague, R. J. M. Finite-Element Modelling of Mechanical Behaviour of Rapid Manufactured Textiles. In *Proceedings of the Institution of Mechanical Engineers, Part L: Journal of Materials: Design and Applications*; 2008; pp 29–36. https://doi.org/10.1243/14644207JMDA161.

[436] Hopkinson, N. *Production Economics of Rapid Manufacture*; 2006. https://doi.org/10.1002/0470033991.ch9.

[437] Sun, L.; Lu, S. The 3D Printing Era : A Conceptual Model for the Textile and Apparel Industry. In *International Textile and Apparel Association(ITAA) Annual Conference Proceedings*; 2015; pp 0–2.

[438] Singh, S.; Ramakrishna, S.; Berto, F. 3D Printing of Polymer Composites: A Short Review. *Mater. Des. Process. Commun.*, **2020**, *2* (2), 1–13. https://doi.org/10.1002/mdp2.97.

[439] ten Bhömer, M.; Tate, D.; Wang, S.; Campanile, F.; Chen, Y. Application of Robust Design Techniques for 3D Printing on Textiles. In *Advances in Intelligent Systems and Computing*; Springer Verlag, 2020; Vol. 975, pp 153–165. https://doi.org/10.1007/978-3-030-20216-3_15.

[440] Jordan, J. M. Additive Manufacturing ("3D Printing") and the Future of Organizational Design : Some Early Notes from the Field. *J. Organ. Des.*, **2019**, *8* (5). https://doi.org/https://doi.org/10.1186/s41469-019-0044-y.

[441] Tronvoll, S. A.; Vedvik, N. P.; Elverum, C. W.; Welo, T. A New Method for Assessing Anisotropy in Fused Deposition Modeled Parts Using Computed Tomography Data. *Int. J. Adv. Manuf. Technol.*, **2019**, *105* (1–4), 47–65. https://doi.org/10.1007/s00170-019-04081-7.

[442] Marangoni, A. G.; Garti, N. An Overview of the Past, Present, and Future of Organogels. *Edible Oleogels Struct. Heal. Implic.*, **2011**, 1–17. https://doi.org/10.1016/B978-0-9830791-1-8.50004-8.

[443] Sedhom, R. V. 3D Printing and Its Effect on the Fashion Industry: It's More than Just about Intellectual Property. *Santa Clara Law Rev.*, **2015**, *55* (4), 865.

[444] Brown, D.; Morgan, M.; McIlhagger, R. A System for the Automatic Generation of Solid Models of Woven Structures. In *Composites Part A: Applied Science and Manufacturing*; Elsevier Ltd, 2003; Vol. 34, pp 511–515. https://doi.org/10.1016/S1359-835X(03)00083-6.

[445] Ribeiro, I.; Matos, F.; Jacinto, C.; Salman, H.; Cardeal, G.; Carvalho, H.; Godina, R.; Peças, P. Framework for Life Cycle Sustainability Assessment of Additive Manufacturing. *Sustainability*, **2020**, *12* (3), 929. https://doi.org/10.3390/su12030929.

[446] Ghobakhloo, M. Industry 4.0, Digitization, and Opportunities for Sustainability. *Journal of Cleaner Production*. Elsevier Ltd April 10, 2020, p 119869. https://doi.org/10.1016/j.jclepro.2019.119869.

[447] Sun, L.; Lu, S. The 3D Printing Era: A Conceptual Model for TheTextile and Apparel Industry. In *International Textile and Apparel Association (ITAA) Annual Conference Proceedings*; IOWA state university: Santa Fe, New Mexico, 2015.

[448] Balletti, C.; Ballarin, M.; Guerra, F. 3D Printing: State of the Art and Future Perspectives. *J. Cult. Herit.*, **2017**, *26*, 172–182. https://doi.org/10.1016/j.culher.2017.02.010.

[449] Saroia, J.; Wang, Y.; Wei, Q.; Lei, M.; Li, X.; Guo, Y.; Zhang, K. A Review on 3D Printed Matrix Polymer Composites: Its Potential and Future Challenges. *Int. J. Adv. Manuf. Technol.*, **2020**, *106* (5–6), 1695–1721. https://doi.org/10.1007/s00170-019-04534-z.

[450] Birtchnell, T.; Urry, J.; Cook, C.; Curr, A. *Freight Miles: The Impacts of 3D Printing on Transport and Society*; Lancaster, United Kingdom, 2013.

[451] Hall, S. Is 3D Printing Increasing the Plastic Pollution Problem? https://www.azocleantech.com/article.aspx?ArticleID=870 (accessed Jun 1, 2021).

[452] Taylor, P. How Green Is My 3D Printer? Scientists Warn Of Heavy Metal Pollution - 3DPrint.com https://3dprint.com/6388/green-3d-printing/ (accessed Jun 1, 2021).

[453] Klarmann, A. Will 3D printing save our environment? https://all3dp.com/will-3d-printing-save-our-environment/ (accessed Jun 1, 2021).

Table 1: Patent award timelines with development years of different additive manufacturing techniques

3DP technology	Patent no	Date of award	Years of development
Inkjet printing (IJP)	US patent 2566443	4^{th} September 1951	Early 1950's
Fused deposition modelling (FDM)	US patent 5121329	9^{th} June 1992	1988-1991
Laminated object manufacturing (LOM)	US patent 4752352	21^{st} June 1988	1985-1991
Stereolithography (SLA)	US patent 4575330	11^{th} March 1986	1986-1988
Selective laser sintering (SLS)	Us patent 4863538	5^{th} September 1989	1987-1992
Laser engineered net shaping (LENS)	US patent 6046426	4^{th} April 2000	1997

Table 2: 3DP techniques and materials

ASTM category	Example of technologies	Materials	Reference
Binder Jetting	3D inkjet technology	Polymers, Composites, Metals, Ceramics.	[99]
Direct Energy Deposition	Laser Engineered Net Shaping (LENS), Laser Deposition (LD), Plasma Arc Melting, Electron Beam	Ceramics, Polymers, Hybrids.	[101, 102]
Material Extrusion	Fused Deposition Modelling (FDM), Fused Layer Modelling (FLM), Fused Filament Fabrication (FFF).	Thermoplastic polymers, Metals, Composites.	[93, 111]
Material Jetting	Continuous Inkjet, Drop-on-Demand (DOD) Inkjet, PolyJet 3DP	Polymers, Ceramics, Composites, Hybrid.	[25, 106]
Powder Bed Fusion	Electron beam melting (EBM), Selective Laser Sintering or Melting (SLS or SLM), Direct Metal Laser Sintering (DMLS)	Polymers, Ceramics, Metals, Composites.	[107]
Sheet Lamination	Ultrasound Additive Manufacturing (UAM), Laminated Object Manufacturing (LOM)	Polymers, Metals, Ceramics, Composites.	[109, 110]
Vat Photo polymerization	Digital Light Processing (DLP), Stereolithography (SLA), Continuous Liquid Interface Production (CLIP).	Photopolymers, Ceramics	[97, 112]

Table 3: List of some software compatible with 3DP technology

3DP stage	Function description	Example of software	Associated 3DP technique	Reference
Pattern making and visualization	To design and simulate 3D fashion products specially garment and provide a virtual yet true to life visualization	**CLO 3D**	N/A	[157]
	To make virtual patterns and prototypes with high efficiency	**Lectra Modaris**	N/A	[156, 158]
	To cover different parts of fashion design including 2D/3D pattern making 3D prototyping for fashion and apparels	**Optitex**	N/A	[159]
3D simulation	To record customized body data recorded by scanner	**Artec Studio 14**	FDM	[174]
	To print final product of customized clothing	**Franklin Software**	FDM	[175]
	To print final product of customized clothing	**CLO Virtual Fashion LLC**	FDM	[174]
	To create virtual product prototype using real world measurement and reference, it can also be used as a 3D modelling tool	**Rhinoceros**	DDP, FDM, DLP, SLA	[8, 30, 147, 161, 166]
3D design and modelling software	To generate 3D CAD data	**Autodesk Fusion 360**	FDM, SLA	[162, 172, 174]
	To generate virtual 3D modelling, animation and visual effects of the design	**Autodesk 3DS Max**	FDM, SLA	[155]
	3D modelling, animation, rendering software. User is capable of shaping 3D objects with intuitive modeling tools	**Autodesk Maya**	FDM, SLA	[163]
	To design auxetic shapes used for printing	**Autocad Inventor®**	FDM, SLA	[27]
	Model different textile and textile-based structures	**Blender™**	FDM, SLS	[164, 167]
	To design the model for 3DP	**Solid Works**	FDM	[165, 175, 176]
	To create virtual design by code based assembly of the parts and design part with different geometries	**Autodesk Tinkercad**	FDM, SLA	[7, 177, 178]
	To process customized body data recorded by scanner	**Geomatic Freefrom Plus**	FDM	[174]
	To model the specimen	**Geomagic Design X**	FDM	[2]
	To design 3D auxetic sinusoidal pattern	**Autodesk 123D**	FDM, SLA	[179]
	To generate 3D model from 3D scanner (zSnapper)	**ViALUX**	FDM	[29]
	To clean, smooth and revise scanned data and provide accurate 3D surface model	**Geomagic Studio 12**	FDM	[29]

Other helper software	To control the ink loaded robot arm and deposit the inks on a mobile platform	**CRTR Robot Editor**	DW	[180]
	To perform the structural analysis of the 3D model	**SolidWorks 2016**	-	[2]
Slicing software	Their main function is to slice the 3D CAD models in to layers and generate data for machine. They transform 3D designs into instruction that 3D printers understand. They convert 3D CAD information in to 2D layer format.	**Ultimaker Cura**	Almost any 3D printing	[1, 169, 175, 176, 181]
		Simplify 3D	FDM	[30, 170, 174]
		Slic3r	FDM, FFF, SLA, DLP	[29, 171]
		Repetier	FDM	[182]
		OctoPrint	FDM	[183]
		KISSlicer	FDM	[184]
		EOS RP tools	SLS	[185]
G-code generator	To create G-Code for printing	**Chitubox**	FDM, SLA	[172]
	To convert 3D pattern into printable G-code file	**Cubicreator**	FDM	[2, 4, 179]

DDM = Direct Digital Manufacturing, DW = Direct Write

Table 4: Different forms of ingredient inks used in 3D printing

State of the ingredients	Typical Polymer material	3DP technique used	References
Powder	ABS	FDM	[189]
Solid filament	PLA	Extruder-heating system	[35][35]
Solid Filament	PLA	FDM	[167]
Solid Filament	ABS	FDM	[202]
Powder	Styrene ethylene butadiene styrene (SEBS)	Material Extrusion	[203]
Solid Filament	ABS	Melt Extruder	[204]
Solid Pellet	HDPE, ABS	Single screw extruder	[205]
Liquid	CNFs	3D Bio-printing	[190]
Powder	Boron nitride powder	3D inkjet printing	[206]

Table 5: Examples of different composite 3DP pastes being used with 3DP techniques

Composite Polymers/ Matrix	Reinforcing Material	Printing Technique	Advantages	Disadvantages	References
Polylactic acid (PLA)	Virgin PLA Polyvinyl Chloride Wood Powder Fe_3O_4 prepared with twin-screw extrusion	FDM	More strength and functional as break elongation improved slightly Reinforcement increases the MFR (melt flow rate) of composite.	Diminution of peak load, break load and strength at break	[197]
Acrylonitrile Butadiene Styrene (ABS)	Fe powder Cu powder Both at varying percentage	FDM	Thermally stable Flexible filaments Applicable in existing FDM300 machine. It withstands more stress than the pure polymeric materials	Greater Fe and Cu powder percentage tends to clog the nozzle of the printer, which needs very expert handling to overcome	[189]
Dimethyl sulphoxide (DMSO)	Raw polyacrylonitrile (PAN) nanofiber	Electrospinning and FDM	Notable improvement of abrasion resistance	The adhesion between the fibre mats and the polymer still needs to be improved without destroying the nano-mat	[211]
Cellulose nanofibrils (CNF)	Carbon nanotubes (CNT)	3D bio printing	Natural composite and mechanical characteristics can be modified across a wide range by choosing a solidification technique	The structure shrinks after drying	[190]
Polylactic acid (PLA)	Cellulose nanofibrils (CNF)	FDM	Natural composites with Increased thermal stability, water absorption and mechanical implementation	The preparation technique of CNF is pivotal for determining the properties of the composite. Mechanical pretreatment is required for the reduction of accumulation in composite	[1]
A blend of polylactic acid (PLA) and polyhydroxy-alkanoate (PHA)	Recycled wood fibres	FDM	Natural composite with the hygro-elastic behaviour of natural fibres	Comparatively weak mechanical features and high hygroscopic sensitivity. As the filament gets thicker, porosity gets increased, but	[195]

				cohesion gets dropped	
Polybutylene Terephthalate (PBT)	Multi-walled carbon nanotubes (CNT)	FDM	Electrically conductive structures and improved thermal stability	The selection of appropriate bed temperature is crucial for successful printing. High printing temperature also leads to wearing the nozzle at a noticeable rate	[208]
Polylactic acid (PLA)	Boron Nitride powder	3D inkjet printing	Enhanced thermal conductivity and greater alignment of BNNSs by the lengthwise direction of the fibre is achieved after the hot-stretching technique	Boron Nitride Nano-Sheets (BNNSs)	[207]

Table 6: Examples of 3DP on the natural and synthetic textile substrate

Fibre source	Fabric composition	The material used for printing	Printing method	Reference
Natural	Woven cotton (plain weave, 100% cotton, 150 g/m^{2})	Rigid cellulose acetate	Direct 3D print	[28]
	Knitted cotton (single knit, 100% cotton, 155 g/m^2) Woven viscose (Bamboo Plain Ivory (BB12), 100% viscose, 140 g/m^2)	Flexible acetoxypropyl cellulose (APC)		
Natural	Woven, 100% cotton Woven, 100% linen	clear 3DP 405 nm UV resin	SLA	[172]
Synthetic	Weft knitted (100% polyester) Weft knitted/coated (100% polyurethane) Warp knitted (100% PET) Weft knitted/coated (100% polyurethane)			
Natural	Woven, 100% cotton	ABS and Filaflex	FDM	[199]
Synthetic	Woven, 100% PET Knitted, 100% PET			
Synthetic	Woven polyester fabric	Doped zinc sulfide pigment as luminous ink, Dielectric ink (a dispersion of titanium dioxide particles), Carbon-containing counter electrode ink	Direct 3D print	[181]
Synthetic	Knitted polyester	Thermoplastic polyurethanes(TPU2-86 85shore hardness)	FDM	[174]
Synthetic	Flat knitted surface (75% Poly-amide 6,6, 18% raw rubber, 7% elastane, 2.7 mm thick, 850 gsm)	Carbonfil 1.75 mm filament Polyethylene Terephthalate	FDM	[29]

Table 7: Summarization based on Yarn/Cell/Texture made by 3DP technology:

Machine/3DP Software	Materials	Procedure/Technique/Method	Reference
CubePro Duo Printer from the cubify company	Lightweight, high impact resistant, and high creep resistant polymer: ABS (Acrylonitrile Butadiene Styrene) filament	Warp and weft yarn made from a thermoplastic filament, ABS, through melting for creating flexible textile structures.	[204]
Stratasy-Objet Connex 3D printer	Polyester and cotton	The texture on cloths can be made by combination of 3DP technology and hand-made fabrication. Ink effects and cracked effects can be a way for creating texture.	[250]
FDM principle-based Mark-Forged 3D printer	Nylon filament	Honeycomb designs were developed in SolidWorks® and uploaded as *stl file format to a 3D printer to create honeycomb cell structure.	[215]
Felting Printer works like Fused Deposition Modelling (FDM)printer	Soft fibres (wool and wool blend)	Yarn like shape was produced by needle felting process (by entangling and compressing sheets of fibres using new custom felting print head which can be attached to Fused Deposition Modeling (FDM)printer also.	[245]

Table 8: 3DP dresses with their designers, fabrication year, materials, 3DP techniques and special features

Dress Name	Designers	Year	Materials	3DP Technique	Features	References
Black Drape Dress	Jiri Evenhuis, Janne Kyttanen	2000	Polyamide	SLS	Fully functional, flexible and breathable	[304]
Crystallization Collection (Look 12)	Iris van Herpen, Daniel Widrig, Materialise	2010	Polyamide	SLS	Rigid, inspired by the transformation of liquid into crystals	[305]
Escapism Collection (Look 2)	Iris van Herpen, Daniel Widrig, Materialise	2011	Polyamide	SLS	lightweight, flexible and lace like structures produced without any needle or thread	[306]
Skeleton Dress	Iris van Herpen, Isaïe Bloch, Materialise	2011	Polyamide	SLS	Rigid dress; the design consists of stylized ribcage, spine motif and pelvic bone	[307]
Hybrid Holism (Look 10)	Iris van Herpen, Julia Körner, Materialise	2012	Acrylonitrile Resin	SLA	Rigid dress, incorporates complex geometrical structures	[307]
Cathedral dress	Iris van Herpen, Isaïe Bloch, Materialise	2013	Polyamide	SLS	Rigid dress, looks like a sculpture of wood	[308]
Anthozoa: Cape & Skirt	Iris van Herpen, Neri Oxman, Stratasys	2013	Polyeurethane Rubber & Acrylic	PolyJet	allowed both hard and soft materials to be printed in a single build	[309, 310]
Voltage Collection (Black Dress)	Iris van Herpen, Julia Körner, Materialise	2013	TPU 92A-1	SLS	Fully flexible dress, developed by superimposing multiple layers of thin woven lines which flows across the body like a woven web	[275]
Wilderness Embodied Collection (Hybrid Dress)	Iris van Herpen, Iris van Herpen, Isaïe Bloch, Materialise	2013	Clear Liquid Resin	SLA	Rigid dress, produced by over-molding 3DP transparent bone-like structures in silicon	[311]

Biopiracy Collection (Look 20)	Iris van Herpen, Julia Körner, Materialise	2014	TPU 92A-1	SLS	Fully flexible dress, moves freely with a glossy sheen	[312]
Magnetic Motion	Iris van Herpen, Niccolo Casas, 3D Systems	2014	Accura ClearVue	SLA	Transparent dress, high level details, covered in crystalline formations	[313]
Hacking Infinity	Iris van Herpen, Niccolo Casas, 3D Systems	2015	Accura ClearVue	SLA	Combination of motion and complexity, 6556 unique individual components continuously react to the body's movement.	[314]
Magma dresses 1 (Lucid Collection)	Iris van Herpen, Niccolo Casas, Materialise	2016	Polyamide	-	Flexible dress, created by stitching together 5000 individual 3DP elements	[315]
Magma dresses 2 (Lucid Collection)	Iris van Herpen, Niccolo Casas, Materialise	2016	TPU 92A-1	-	Flexible dress, formed "fine web" combining flexible TPU printing with polyamide printing	[316]
Foliage dress (Ludi Naturae Collection)	Iris van Herpen, TU Delft	2018	thermosetting polymers, tulle fabric	PolyJet	Flexible dress, tulle fabric was inserted after printing several layers, followed by printing of the next layers on top	[274]
Liberty Leading the People Collection	Danit Peleg	2015	FilaFlex by Recreus	FDM	Flexible dresses, printed by home printers	[290]
Paralympics Dress (The Birth of Venus Collection)	Danit Peleg, Gerber Technology	2016	FilaFlex by Recreus	FDM	Flexible, comfortable jackets that moves freely	[295]
Liberation Collection	Julia Daviy	2018	70A TPE, Flexible Resin	FDM, SLA	flexible, comfortable, fashionable, innovative & everyday wearable	[317]
Bahai Dress (MER KA BA collection)	threeASFOUR, Bradley Rothenberg, Materialise	2013	Resin	FDM	Rigid, Flat Pattern pieces of Fractal interlocking weave	[282]
Harmonograph Dress	threeASFOUR, Travis Fitch, Stratasys	2016	Agilus30, VeroBlack	PolyJet	Flexible, durable, made of interwoven structure, circle of the spiral follows geometry of Fibonacci sequence	[284]

Oscillation Dress	threeASFOUR, Travis Fitch	2016	Agilus30, VeroCyan, VeroWhite	PolyJet	Flexible, made of interwoven, interlocked structures derived from vibrational & frequency geometry	[285, 318]
Pangolin Dress	threeASFOUR, Travis Fitch, Stratasys	2016	Agilus30, VeroBlack	PolyJet	Flexible, durable, comprised of 14 pattern pieces, made of interlocking weaves	[284]
Kinematics Dress	Jessica Rosenkrantz, Jesse Louis-Rosenberg, Shapeways	2014	Nylon	SLS	Breathable, stretchable, made of triangular panels interconnected by hinges, can move and flow, printed in one piece through folding	[288, 319]
Kinematic Petal Dress	Jessica Rosenkrantz, Jesse Louis-Rosenberg, Shapeways	2016	Nylon	SLS	Flexible, made by interconnecting 1600 unique pieces by more than 2600 hinges, aggregated rigid components react as continuous textile, printed in one piece through folding	[289]
inBloom Dress	Lim Kae Woei and Elena Low Lee Wei (XYZ Workshop)	2014	Flexible PLA Filament	FDM	longest 100% desktop 3DP dress, created from a primary mesh of a geometric floral motif, made of 191 panels	[320]
Loom Dress	Maria Alejandra Mora Sanchez	2018	TPU	FFF	a flexible, expandable, adapts to body change, ready-to-ware, comfortable	[321]
Dive into Me	Melinda Looi, Samuel Canning	2013	Polyamide	SLS	Floor-length gown with more than 5,000 crystals molded into 3DP ‘fabric’, printed in single part	[322, 323]
Verlan	Francis Bitonti, MakerBot	2013	MakerBot Flexible Filament	FDM	referenced muscle fibres, veins and arteries to an inside-out body	[324]
Bristle Dress	Francis Bitonti, MakerBot	2014	MakerBot Flexible & Natural PLA Filament	FDM	The top of the dress is big volume, cloud-like translucent haze and the skirt suggests lace-like origami.	[325]
Dita’s Gown	Francis Bitonti, Michael Schmidt Studios, Shapeways	2013	Nylon	SLS	Flows with the body, nearly 3000 unique articulated joints detailed with 13,000 black Swarovski crystals	[326, 327]
Snow Queen	Victoria's Secret, Bradley Rothenberg (Shapeways)	2013	Nylon	SLS	Rigid, festooned with thousands of Swarovski crystals	[328]
Smock Corset	Julia Koerner, Marina Hoermanseder	2015	Liquid Resin	SLA	Historic corset design with a spectacular 21st century twist	[329]
Sporophyte C ollection	Julia Koerner, Stratasys	2015	TangoBlackP lus and VeroBlack	PolyJet	Inspired by natural structures found in fungi and kelp, allows for flexibility via a combination of rigid and rubber-like structures	[330]
Néobaroque Collection	Pia Hinze	2013	Nylon 12	SLS	Rigid, organic shapes like flourishes were printed in parts and then assembled	[331]

Wanderers collection	Neri Oxman, Christoph Bader, Dominik Kolb	2014	VeroCyan, VeroClear, VeroMagenta, VeroYellow	PolyJet	3DP wearable capillaries are infused with synthetically engineered microorganisms to make the hostile habitable and the deadly alive. They are designed to interact with a specific environment and generate sufficient quantities of biomass, water, air and light necessary for sustaining life from elements that are found in the atmosphere	[332]
Lady Gaga's Anemone dress	Benjamin Males, Studio XO	2013	Polymer Resin	SLA	Rigid, blows large and small bubbles	[48, 300]
Spider Dress 2.0	Anouk Wipprecht, Philip H. Wilck	2015	Nylon 12	SLS	equipped with an Intel Edison chip that reads biosignals to defend the wearer's personal space	[333]
Hard Core Vein 2.0	Maartje Dijkstra, Creative Industries Fund NL	2014	Transparent PET filament	-	Made of tubes filled with ink that pump with beats of music, "like blood through a vein on a heartbeat"	[334]
Synapse Dress	Anouk Wipprecht, Niccolo Casas, Materialise & Intel Edison	2014	TPU 92 A-1	SLS	flexible, comfortable and reads body signals, and proximity of other people to respond in an intuitive manner.	[301]
Smoke Dress	Anouk Wipprecht, Niccolo Casas, Materialise & Intel Edison	2013	TPU 92 A-1	SLS	Demonstrates a dialogue between the wearer and the environment by producing a smoke veil when it is interrupted by someone else	[335]
Caress of the Gaze	Behnaz Farahi	2015	Shore 60 Black, Vero White	PolyJet	Flexivle, responds to the gaze of others by moving the gazed parts of the dress	[302]

Table 9: Different protective gears developed with 3DP technology

Protective Gear	3DP Component	Materials	3DP Technique	Application Area	Reference
Protective Face Mask	Reusable mask and filter membrane	Polyamide composite	Selective Laser Sintering (SLS)	Human face	[336]
Personal Protective Gear	Knee and Crotch protective components	Thermoplastic polyurethane	Additive Manufacturing (AM, Desktop 3DP)	Knee, hip joint, elbow, Crotch protector etc.	[2]
Protective Pads	Fall impact protection pad	Thermoplastic polyurethane (NinjaFlex)	Fused Deposition Modelling (FDM)	Human body parts vulnerable to fall impact	[4]
Safety Protective Clothing	Elbow and knee protective 3D shaped component	Shape memory thermoplastic polyurethane	Fused Deposition Modelling (FDM)	Elbow, Knee, etc.	[179]

Table 10: Some recently 3DP substrates for application in the field of electrodes and microelectronics

Application Type	Material Used	3DP Technique	Application/advantage	reference
Strain sensor	Single-walled carbon nanotube composite(SWCNT)	Ultraviolet facilitated direct-write (UV-DW)	*Sensors are very susceptible to minute mechanical interferences, which is very desirable. *Freestanding geometry of the sensors has the potential to truncate the effect of an unprecedented stimulant on the result	[341]
Liquid sensor	PLA/MWCNT (Multi-wall carbon nanocomposite)	SC3DP	*Relatively High electrical conductivity. *Excellent sensitivity even for a short dipping	[346]
TRGO (thermally reduced graphene oxide) electrodes	GO (graphene oxide)-letter converted into TRGO ink through HPH (high-pressure homogenization)	3D micro extrusion	*Devoid of binder and surfactant-free electrodes. *Tolerance of high viscosity. *Graphene-based EC(Electrochemical capacitor) gives a cutting-edge performance in comparison to electrolytic capacitors	[343]
Titanium interdigitated electrodes	Ti–6Al–4 V metal powder	SLM (Selective laser Melting)	*Micro-super capacitors based on this interdigitated structure have high energy storage capacity for the additional third dimension.	[344]
Biosensors	Conductive hydrogels or conductive hydrogels precursor	3D bio plotting/light-based printing, stereolithograph y (SL/SLA), direct laser writing (DLW) or DLP/Ink-Jet printing	Tissue engineering, wearable electronics, stability of the shape of the printed structure.	[347]
Nanocomposite supercapacitors, strain gauge sensor	Solution of photopolymers filled with titanium and silver nanoparticles	Inkjet printing	Enhanced mechanical property, electrical conductivity, thermal	[348]

			stability and gas barrier properties.	
Flow sensors	Hydrogel nanocomposites filled with polydiacetylene nanoparticles	Dynamic optical projection stereolithography (DOPSL)	Enable rapid, low cost and customized fabrication.	[349]
Electronic sensors	Thermoplastics (PLA or ABS) filled with hydroxyapatite, nano clay or Nanocrystalline	Fused deposition modelling (FDM)	Single build method devoid of any complex and expensive materials.	[350]
Microelectronics, antennas	Conductive ink of silver nanoparticles, photopolymers incorporated with nanotubes.	Conformal 3DP (C-3DP)	Potential for order of magnitude augmentation over basic monopole designs.	[351]
sensing applications, MEMS (micro-electromechanical system), microelectronics	Photopolymers (urethane, epoxy) filled with nanotubes	Ultraviolet 3D printing	Creation of complex and miniature geometry with enhanced mechanical, thermal, optical property.	[352–355]
Hollow capacitive sensor, smart structure with shape memory effect, stretchable spring circuits	Photocurable resin with MWCNTs	Digital light-based 3D printing(DLP)	Layers can be formed rapidly in this method, potential to reshape the final properties.	[143]
Capacitive sensor	Ionically conductive PAAm-PEGDA(polyacrylamide - poly ethylene glycol diacrylate) hydrogels.	Digital light-based 3D printing (DLB3DP)	Sensing both pressure and strain, high sensitivity, surface quality require no additional supporting structure.	[356]
Solid-state flexible super capacitors	Graphene Oxide(GO)	Screen printing	Excellent mechanical stoutness, avoid the inconvenience linked to fabricating devices with conductive yarn	[357]
Capacitive soft strain sensor (CS3)	Non-volatile conductive ionic fluid modified soft silicone elastomer	Multicore-shell fibre printing	Sensors with meticulous and hysteresis-free dispatching in both stable and unstable operating conditions	[358]

Table 11: Test methods and international standards associated with various 3DP testing

Standard	Title	Objective	Scope for 3DP on textile	Reference
ISO Standards				
ISO 6133:2015	Rubber and plastics – Analysis of multi-peak traces obtained in determinations of tear strength and adhesion strength	Determine the tear strength and adhesion strength of vulcanized rubber or fabric coated with or attached to rubber or plastics. The standard calculates the median and range of peak value from a graphical plot of force versus time. It ensures more uniformity in the evaluation and presentation of test results.	The adhesion depends on the inter-fibre friction between yarn and the polymer substances. By this standard, the adhesion strength of some rubber or plastic materials on a specific textile fibre could be determined according to the application of the end product.	[238, 372]
ISO 13934-1:2013	Textiles – Tensile properties of fabrics Part 1:Determination of maximum force and elongation at maximum force using the strip method	The maximum force and elongation at the maximum force of textile fabrics are determined in this standard by using the strip method. Applicable to woven fabrics as well as stretched fabrics with elastomeric fibre imparting with mechanical or chemical treatment. Coated fabrics, nonwovens geotextiles, textile-glass woven fabrics, fabrics inherent carbon fibres, or polyolefin tape yarns are not applicable in this standard.	The standard assists to optimize the theoretical & statistical model of fabric properties and some other factors like printing temperatures on stress, strain, and deformation of printing materials deposited on textile fabric through the 3DP process.	[30, 373]
ISO 12947-2:2016	Textiles – Determination of the abrasion resistance of fabrics by the Martindale method – Part 2: determination of specimen breakdown	Specifies the procedure of identifying the specimen breakdown (end-point of the test) by inspection at fixed intervals. All textile fabrics, including nonwoven and specifiers having low wear life, are applicable here. On the other hand, it does not apply to coated fabrics, including laminated fabrics.	Applying the Martindale test with a specific amount of rubbing cycles determines the loss of thickness of different printing substances. Thus proper materials could be selected under the correct specification of 3DP textile products.	[174, 374]
ISO 15797:2017	Textiles – Industrial washing and finishing procedures for testing of workwear	For testing colour characteristics, dimensional stability, seam puckering, creasing, pilling, and visual aspects, this standard has been used. It uses defined intermediate scale equipment and exacts test procedures that could be used for the evaluation of workwear intended to be laundered industrially.	In order to introduce new functional development in the workwear sector, fastness to washing & wash resistance is a demanding requirement for the 3DP process.	[174, 375]
ISO 2411:2017	Rubber- or plastics-coated fabrics – Determination of coating adhesion	The standard specifies a method of determining the coating adhesion strength of coated fabrics. Due to inadequate adhesion strength, delamination may occur and fails the product.	Resultant form-locking connection & effective polar interaction between yarn and print polymers contribute to the amount of adhesion force.	[174, 376]
ISO 11339:2010	Adhesives – T-peel test for flexible-to-flexible bonded assemblies	To determine the peel strength of an adhesive, this international standard is used. It measures the peeling force of a 'T' shaped bonded assembly of two flexible adherents. Metal adherents and flexible adherents may use this method.	In order to explain polymer-to-polymer adhesion, different types of theories can be applied under different conditions between two flexible adherents in this specific standard.	[369, 377]

ISO 527-3 :2018	Plastics – Determination of tensile properties – Part 3:Test conditions for films and sheets	This standard specifies the condition to determine the tensile properties of plastic films or sheets less than 1 mm thick. The method is not suitable for cellular materials and textile fibre reinforced plastics.	The tensile strength of various filaments of different companies could be examined. The method can determine the delamination force of the fused layer and the force needed to break the partially fused layer inside.	[216, 378]
ISO 6330:2012	Textiles – Domestic washing and drying procedures for textile testing	These washing and drying testing procedures are applicable for textile fabrics, garments, or other textile articles of appropriate combinations. The standard also specifies the reference detergents and ballasts.	After implementing this international washing procedure, some important parameters like tensile resistance, stress at rupture &durability could be checked for the feasibility of the 3DP process.	[30, 379]
ISO 5084:1996	Textiles – Determination of thickness of textiles and textile products	The standard measures the thickness under a specified pressure. It does not apply to textile floor coverings, nonwovens, geotextiles, and coated fabrics.	The stress, strain, tensile force, and other related properties depend on the thickness of the textile fabric. This is the reason for executing the international standard.	[30, 380]
ISO 604:2002	Plastics – Determination of compressive properties	Here the compressive properties have been determined under some defined conditions like a standard test specimen and a range of test speed. The length of the specimen has to be adjusted to prevent buckling under load.	The test determines compressive behaviour, compressive strength, compressive modulus, and the compressive stress-strain relationship of 3DP textiles. The compressive strength is related to the infill ratio, tensile & shock absorption properties.	[2, 381]
ISO 527-1:2019	Plastics – Determination of tensile properties – Part 1: General principles	The methods are used to check the tensile behaviour of the test specimens like tensile strength, tensile modulus, and other aspects of the stress/strain relationship of plastics and plastic composites under defined conditions.	The methods of determining tensile properties are suitable for rigid, semi-rigid moulding, extrusion & cast thermoplastic material, filled & reinforced compounds, whereas not suitable for rigid cellular material.	[370, 382]
ASTM Standards				
ASTM D575 – 91(2018)	Standard Test Method for Rubber Properties in Compression	To compare the stiffness of rubber materials in compression, this standard is used. The legal aids to develop rubber materials for the compressive application.	This mechanical testing in 3DP shows the behaviour of the composites according to the iso-stress model while in compression.	[246, 383]
ASTM D1238	Standard Test Method for Melt Flow Rates of Thermoplastics by Extrusion Plastometer	The test particularly uses for quality control tests for thermoplastics. It serves to indicate the uniformity of the flow rate of the polymer.	The Material Flow Rate has been tested in 3DP for different proportions of reinforcement & virgin polymers by maintaining standard conditions.	[197, 384]

ASTM D5034	Standard Test Method for Breaking Strength and Elongation of Textile Fabrics(Grab Test)	To determine breaking force and elongation for acceptance testing of commercial shipments of most woven and nonwoven fabrics in trade.	There is an effect of extrusion speed, temperature as well as fill density of 3DP substances on tensile strength testing.	[175, 385]
ASTM D5170	Standard Test Method for Peel Strength("T" Method) of Hook and Loop Touch Fasteners	This test method determines the measurement of the peel strength of hook and loop touch fasteners using a tensile testing machine recording constant-rate-of-extension.	The 3DP material could be evaluated in terms of the average peak load long with the 180°delamination test. The inch-pound units are used as standard.	[198, 386]
ASTM D570	Standard Test Method for Water Absorption of Plastics	It covers the determination of the relative rate of absorption of water by all types of plastics (cast, hot/cold moulded, etc.) when immersed.	The moisture content of printing material is related to properties like electric insulation, dielectric losses, mechanical strength, appearance & dimensions.	[205, 387]
ASTM D3763	Standard Test Method for High-Speed Puncture Properties of Plastics Using Load and Displacement Sensors	They are designed to provide load versus deformation response of plastics under essentially multi-axial deformation conditions at impact velocities.	Assist in determining puncture properties of rigid 3DP substances over a range of test velocities, thus appropriate in engineering design as well.	[153, 388]
ASTM D6110	Standard Testing Method for Determining the Charpy Impact Resistance of Notched Specimens of Plastics	The resistance of plastics to breakage by flexural shock is determined as indicated by the energy extracted from standardizing pendulum-type hammers, mounted in machines, in breaking standard specimens with one pendulum swing.	Energy losses due to fracture propagation, vibration, friction between the striking nose and the specimen have the potential to become significant while testing with 3DP material.	[153, 389]
ASTM D790-03	Standard Test Methods for Flexural Properties of Unreinforced and Reinforced Plastics and Electrical Insulating Materials	Determination of flexural properties of unreinforced and reinforced polymer substances, as well as high modulus composites and electrically insulating polymer, moulded or cut from sheets, plates, or moulded shapes.	This flexural properties testing method is applied for both rigid and semi-rigid material whereas not applied for materials that do not break within the 5% strain limit.	[72, 390]

Table 12: Different optimisation techniques to determine optimum FDM process parameters

Observed printed part behaviour	Process parameter	Optimisation technique	Reference
Dimensional accuracy	Build orientation, raster angle, layer thickness, the width of the print, air gap, extrusion and filling speed.	Grey taguchi method, Grey relational grade (GRD), Artificial neural network (ANN), Fuzzy logic.	[398–401]
Surface roughness	Deposition speed, layer thickness, print width, raster angle, air gap, model temperature, filling style.	Taguchi's design matrix, Analysis of variance (ANOVA), the signal to noise ratio (S/N), Coded genetic algorithm (GA), Full factorial design.	[399, 402–404]
Mechanical behaviour	Print orientation, air gap, material temperature, print width, material colour, the thickness of the print layer, raster angle, immersion time in chemical,	Full factorial design, fractional factorial design, Group method of data handling (GMDH), Analysis of variance (ANOVA), Central composite design (CCD), Differential Evolution (DE)	[393, 405–408]
Manufacturing duration	Print orientation, contour width, print width, raster angle, layer thickness.	Coded genetic algorithm (GA), Taguchi's design matrix, Orthogonal array (OA), Analysis of variance (ANOVA), Full factorial design	[403, 409, 410]
Material behaviour	Air gap, raster angle, layer thickness, print width, scan speed	Orthogonal array (OA), Analysis of variance (ANOVA), Signal to noise ratio (S/N), Taguchi method, Main effect analysis, Response surface methodology (RSM).	[411–413]

Table 13: Effect of infill material & percentage on the hardness of the 3DP part

Materials	*Increase in composite infill*	*Effect on Hardness*	*Reference*
PLA Matrix + PVC	PVC	Decreases	[197]
PLA Matrix + Wood Powder	Wood powder	Decreases	
PLA Matrix + Fe_3O_4 Powder	Fe_3O_4	Increases	

Table 14: Layer thickness with nozzle diameter for different 3D printers

Printer Name	3DP Technology	Print Material	Layer thickness (mm)	Reference
Orcabot XXL	FDM	PLA	0.2	[211]
		PLA and Soft PLA		[238]
Cubicon Single	FDM	NinjaFlex®	0.2	[4]
EOS Formiga P1	SLS	Nylon	0.1	[185]

Table 15: Typical maximum print size capacity utilized by different designers

AM technique	*Print Size (Maximum) mm*	*Brand/Designer*
FDM	490 X 390 X 200	***Iris Van Herpen***
SL	2000	***Iris Van Herpen; Lady gaga***
SLS	80 X 95	***Dr. Richard Hoptroff***

Table 16: Speeds of different 3D printers with different print materials (For FDM technique)

3D Printer	3DP Material	Printing Speed (mm/s)	Reference
Cubicon Single Plus FDM printer	TPU and SMTPU	50	[179]
M3036 FDM Desktop Printer	PLA/PEG600/CNF Biocomposite	40	[1]
Ocrabot XXL	Filaflex	50	[7]
Hermes X1 Model	PLA monofilament	40	[161]
MakerBot Replicator 2x	PLA	100	[168]
Cubicon Sinlge	NinjaFlex®	40	[4]
WANHAO Duplicator 4/4x	PLA-Carbon Black (CB) fillers	60	[30]
Cubicon Desktop 3D printer	TPU filament	10	[2]

TPU = Thermoplastic polyurethane, SMTPU = Shape memory thermoplastic polyurethane, PLA = Poly Lactic Acid, PEG = Poly ethylene glycol, CNF = Cellulose nanofibrils

Table 17: Direct comparison of the print duration required to print same 3D shape by FDM and DLP 3DP technique [147]

3D Printer	**3DP material**	**Print duration**	**Reference**
DLP	Polyurethane acrylate photopolymer	9 min 37 s	[147]
FDM	ABS	204 min 31 s	

ABS = Acrylonitrile butadiene styrene

Table 18: Nozzle and print bed temperature of different FDM 3D printers with different print materials for FDM technique

Print Materials / Composites	Nozzle Temperature (°C)	Bed Temperature (°C)	Reference
TPU	230	0	[179]
SMTPU	230	50	[179]
PLA-Keratin composite	190	Room temperature	[176]
Nylon white (Nylon 6)	275	Not heated	[153]
PLA/PEG600/CNF Bio composite	210	Not heated	[1]
PLA Monofilament	215	60	[161]
Filaflex	245	65	[7]
Filaflex	245	Not heated	[199]
PLA	190-210	Room temperature-80	[211]
PLA	230	65	[168]
NinjaFlex®	230	40	[4]
PLA and Soft PLA	200	60	[238]
TPU filament	230	50	[2]
ABS	240	Not heated	[199]

TPU = Thermoplastic polyurethane, SMTPU = Shape memory thermoplastic polyurethane, PLA = Poly Lactic Acid, PEG = Poly ethylene glycol, CNF = Cellulose Nano fibrils

Table 19: Methods related to the improvement of adhesion for 3DP

Methods	Materials	Testing	Printing Method	Reference
Increasing adhesion strength by the polymer coating	1.Cotton woven fabric 2.Poly-lactic Acid (PLA) (5% dissolved in hot 1,2-dichlorobenzene) 3.Acrylonitrile Butadiene Styrene(ABS) (5% dissolved in acetone) 4. Poly-methyl methacrylate(PMMA), 5% dissolved in acetone) 5.Polyamide(PA) (Soluble amorphous co-polyamide from Îµ-caprolactam, hexane-1,6-diamine, hexanedioic acid and 4,4-diaminodicyclohexylmethane, 5% dissolved in 80% ethanol and 20% water).	Performing adhesion test was carried out by using a universal testing machine. This is following DIN 53530, assessed following the ISO 6133 and applying the method for more than 20 peaks.	3DP was performed via Fused Deposition Modeling (FDM) 3DP technology using Orcabot XXL 3D printer with 0.4 mm nozzle diameter, 0.2 mm layer thickness, 200 °C nozzle temperature for PLA and 220 °C for (ABS) and 60 °C printing bed temperature.	[237]
Improved adhesion by textile surface treatment (e.g. washing, roughening, finishing, and plasma) to treat the textile product surface characteristics like wettability or hairiness.	1.Flexible materials for printing: For example, Soft PLA and a thermoplastic elastomer (TPE), 2.Enzyme amylase and the washing agent Kieralon CD (BASF), 3. Polyester, cotton and wool, argon (Ar) and nitrogen (N2), carbon dioxide (CO_2) for plasma treatment.	Accomplishment of adhesion test by separating layers of laminated woven fabrics according to DIN 53530, using a testing device called Zwick Roell.	Fused Deposition Modeling (FDM) 3DP technology was applied with the FDM printer X400 manufactured by German RepRap GmbH.	[68]
Using NaOH (Sodium hydroxide) to improve adhesion between PLA matrix and reinforcement	1.Polylactic Acid (PLA) filament (natural colour, 3mm), 2.Keratin bio-fibre (reinforcing natural material), 3.Sodium Hydroxide	The storage modulus (E') and the tan delta (Tan δ) were used as a temperature function of the composites were evaluated by DMA(Dynamical mechanical analysis)	The 3DP composites were manufactured using an extrusion-based 3D printer (Industria 55, Queretaro, Mexico).	[176]
Form-locking connections to improve adhesion forces	1.PLA (Poly-lactic acid) 2.The knitted fabrics which made by Polyester (PES), Polyamide / Nylon (PA/Nylon), Polyacrylonitrile (PAN)	According to DIN 53530 standard, adhesion tests were executed and appraised according to ISO 6133 by using 20 peaks for obtaining adhesion related results.	FDM printer named Orcabot XXL manufactured by Prodim (The Netherlands) was used for 3DP.	[210]
By maintaining 90Â° infill orientation for increasing adhesion force	1. Cotton woven Fabric 2. Glue stick 3. Hairspray 4. Acetone (1 h, afterwards washing in water) 5. NaOH (30 s in 0.2M NaOH, afterwards washing in water)	Adhesion was measured according to 53530 & results were evaluated according to ISO 6133 using more than 20 peaks.	Printing PLA polymer using FDM printer named Orcabot XXL on cotton woven fabric.	[236]

	6. 400 grit size abrasive paper 7. PLA, ABS or nylon			
Decreasing Z-distance (the distance between the nozzle and the printing bed) for increasing adhesion	1.PLA 2.Different cotton woven fabrics	According to DIN 53530, adhesion tests were executed & ISO 6133 was used to evaluating the result	3DP was done by using an FDM printer named Orcabot XXL with PLA printing material on different cotton woven fabrics by varying thickness	[242]
Increasing yarn density, i.e. the number of warp threads per centimetre for high adhesion	1.Polyamide 66 (PA66) and polylactic acid (PLA) fabric, 2.PLA, PLA nano-composites, nylon 3.Nanosize carbon black/PLA (CB/PLA) and multi-wall carbon nanotubes/PLA (CNT/PLA) nanocomposites	Using a standard test method following SS-EN ISO 11339:2010, using a Zwick/Z010 tensile tester, adhesion tests were performed with a 100 mm/min separation rate.	Deposition of polylactic acid (PLA) on Polyamide (PA) was done by FDM technique.	[220]

List of figure captions: