CHAPTER 4

3D Printing and Additive Manufacturing in Fashion

Lushan Sun

Abstract The growth of 3D printing (3DP) has escalated, enabling it to become an integral part of forefront innovations and explorations in fashion. This chapter introduces a holistic view of the contemporary advancements and prospects of 3DP and additive manufacturing in the fashion supply chain through the perspective of direct digital manufacturing and the technology-driven fashion network. The author's research in wearable product developments also provides insights into the advantages and challenges of 3D CAD and 3DP materials, and the interdisciplinary approaches expected in adapting and promoting 3DP innovation. Simultaneously, it demystifies the application potentials and values of 3DP in fashion through three prime and practical case studies. Each case study deals with the perspective of product design, product technology, production capabilities, and product promotions for retail.

L. Sun (✉)
The Institute of Textiles and Clothing, The Hong Kong Polytechnic University, Hunghom, Kowloon, Hong Kong
e-mail: sarina.sun@poly.edu.uk

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Introduction

Since the 1980s, additive manufacturing technology has been patented and utilized in industrial applications for several decades. Today, it is recognized for its value as a technology that resulted in reduced lead time in mass manufacturing and product customization, sustainable practices, and innovative potentials in diverse fields, such as architecture, culinary, biomedical, and consumer. The technology has also been redefined with new materials, material forms, and technology advancements to accomplish high-quality outcomes. Traditionally, it was known as a rapid prototyping technology, but presently, it is more commonly referred to as 3D printing (3DP), which is a form of additive manufacturing and direct digital manufacturing (DDM) (Sun & Zhao, 2017).

In the fashion industry, 3DP has been explored for roughly two decades now, primarily spearheaded by design research leaders in innovative explorations. Some of them include Iris van Herpen, Nike, Nervous Systems, Continuum Fashion, Francis Bitonti, XYZ Workshop, Julia Koerner, Neri Oxman, and Pringle of Scotland that continue to propel 3D printed fashion in the market. Today's 3D printed fashion often involves interdisciplinary collaborations and approaches that generally require the involvement of experts from architecture, industrial design, fashion, interior design, computer science, media art, interactive design, and biological engineering. From the early focus emphasizing the application of 3DP in fashion accessories (e.g., jewelry, wearable art) to the modern ready-to-wear fashion products for consumer customization and mass production, the technology has undergone several stages of progression. The technology continues to evolve at an exponential rate.

At the same time, designers are adapting by demonstrating greater versatility in their knowledge (e.g., 3D CAD, new materials), the fashion supply chain supporting 3DP is developing to become more agile, and consumers are becoming more hands-on and acquiring an interactive role in their own product design and customization. The current technology innovation in 3DP is well supported by Jin and Cedrola's (2018a) argument that "3D printing allows for the creation of custom-built designs, which may include complex products without high capital investments. It reduces the lead time associated with projects as the design and production process is shortened" (p. 23). Grounded by the concept of product and process innovation described by Jin and Cedrola (2018b, 2019), this chapter presents the current and future potential and the value of various 3DP technologies. Further, the way 3DP is modified to adapt to the modern market through three practical case studies has been expounded.

Direct Digital Manufacturing in Fashion

Advantages and Challenges in 3D Printing and Materials

As the applications of 3DP technologies expand, modification of materials and methods for greater comfort and functionality in fashion products is gaining traction in the retail environment. Typically, designers work with four major types of 3DP technologies in apparel, accessories, and footwear, which are (a) fused deposition modeling (FDM), (b) vat polymerization, including stereolithography apparatus (SLA) and direct light processing (DLP), (c) material jetting, and (d) selective laser sinter (SLS). The most popular and frequently employed printing method for apparel design is the FDM technology. The fused deposition printer relies on depositing filaments of various diameters through one or more nozzles and builds an object on a flat plate (Lipson & Kurman, 2013), which is somewhat streamlined in the mechanical configuration. The printing quality generally depends on the nozzle size, filament feeding speed, printing resolution of the printer, object complexity, object position, type and diameter of filaments, and different support structure selections (Lipson & Kurman, 2013). Often, complex or intricate objects, depending on their position, require a thin layer of support material to secure the hollowed parts in place during the printing process. The choice of materials for FDM commonly used for fashion products are polylactic acid (PLA), polyamide (nylon), and thermoplastic polyurethane (TPU), which often provides an expansive range of color options.

Apart from the complex variables in the FDM printer settings, the material choices, such as TPU or nylon, may prove to be slightly challenging to regulate in different levels of humidity and temperatures. At times, the material requires pre-treatment or post-processing to ensure optimal print quality and efficiency. The final prints may also require post-finishing, such as dislodging supporting materials for intricate structures through water dissolution or manual cutting and sanding. Color dyeing or coating also can be applied in post-finishing prints (Sun, 2018). The advantage of using FDM 3DP resides in its relatively simple mechanics, which enables versatility in hacking or modifying different design processes and materials combinations. More popularly, designers and researchers consider it to be an ideal choice for 2D or flatter structures in over-printing to combine or fuse with alternative substrates, such as conventional textiles for unique textile functions and aesthetics (Julia Daviy, n.d.; Technical Research Centre of Finland [VTT], 2015; Tucker, 2015).

Second, vat polymerization techniques, stereolithography apparatus (SLA) and direct light processing (DLP), are the other most frequently utilized technology, often implemented for the purpose of footwear and accessory production. It is a process that involves a UV light source curing liquid resin or photopolymers to form solid layers. SLA and DLP are very similar in their general mechanism, except that the DLP process involves operating a digital light projector screen for projecting an image of each layer and is considerably faster than SLA. Presently, advanced vat polymerization technology also includes the Digital Light Synthesis™ (DLS) by Carbon (Adidas, 2019) and a few others worldwide. DLS employs a photochemical process that enables light to project through an oxygen-permeable film into a vat of liquid resin. The choice of material varies from rom ridged and rubbery to flexible. Additionally, more than 30 material variations are available in some of the advanced models. Currently, the vat polymerization methods require a separate machine for curing, which may demand additional space and labor investment for the procedure. However, so far, it is the most economical and efficient technology that delivers market-ready quality builds. The downside of the technology is that it is not capable, at the moment, for larger building volume and is more appropriate for printing structural objects.

Third, providing more flexibility and versatility in a high-resolution material mixture, the material jetting 3DP technology is a common option for multi-material fabrication (Lipson & Kurman, 2013). The technology uses liquid resin drops, building, and dissolvable support material to cure on a building plate. The build outputs are generally smooth in texture and can be matt or glossy. Different material variations, such as PLA and TPU, can be preset for various mechanical qualities and color combinations to further customize material performance and the overall visual designs. However, the material jetting technology is associated with high costs compared to the FDM and SLA methods. It also requires post-finishing steps, which may increase labor costs. Despite the expense, the print outcome using this technology is high in resolution, which makes it a market-ready quality.

The last type of 3DP technologies is selective laser sintering (SLS), which is a laser-based powder fusing process (Lipson & Kurman, 2013). The bottom of a building chamber, which may vary in size, moves down as the object forms through sintering. Typically, a roller is designed to continually add and smoothen each layer of sintered powder. The most common materials for SLS are nylon and TPU that print with a porous surface, but only basic neutral color options are available. The same powder material in SLS functions as the building and supporting material for the builds. Depending on the material, up to 70–80% of the used powder can be blended with virgin powder for the next printing job. For most fashion product developments, SLS requires high maintenance and is time-consuming and expensive. Traditionally, SLS relies on large industrial-grade systems but is now available with several desktop options for small studio environments. In some cases, such as in the case of small accessory production, SLS can be suitable for highly complex or intricate details, articulating structures, and multiple-unit printing.

Advantages and Challenges in 3D CAD

One of the fundamental advantages of 3DP is enabling the production of highly complex structures in an efficient production process (Sun & Zhao, 2017). First, 3D CAD models can be readily scaled and modified digitally for changes and improvements, which essentially instills sustainable practices into the 3DP design process. With the aid of 3D scanning technology, reverse engineering techniques may prove to be more convenient and time-saving in building a basic object silhouette and defining parameters. In advanced CAD systems, 3D simulation technology can help visualize the final design with articulating structures (Nervous System, 2014). Depending on the specific 3DP method (e.g., SLS, FDM) chosen, designers need to evaluate the feasibility of materials and 3D CAD designs accordingly.

The increased complexity in fashion products essentially disrupts the conventional design flow from the perspectives of both the apparel design and 3DP. Therefore, the designer must majorly consider the material structure in terms of how it influences the function of the final garment. The following essential questions must be posed first: (a) How does the material structure visually impact garment aesthetics and styles? (b) How does it interact with traditional textiles and other construction notions, such as zippers and elastic? and (c) How does it provide comfort and maximize performance for the wearer? Furthermore, material performance and evaluation are the other critical factors concerning the potential obstacles in the application of the 3DP technology for activewear. As more novel design processes are integrated, more options of various evaluation criteria to assess the material property and performance will be available, which makes 3DP appreciably more feasible in 3D printed fashion.

Presently, most 3D CAD tools for 3DP are not developed for fashion products with organic forms that involve material considerations for the human body. First, a conventional 3D CAD environment involves an x–y-z coordinate system that builds through object curves, surfaces, and solids parameters. The design logic in 3D CAD modeling is drastically different from the average 2D CAD programs used in fashion design. Currently, there are two common approaches applied in 3D modeling of fashion products. One is the direct or primitive 3D modeling method, in which most objects are developed manually in 3D CAD programs (e.g., Rhinoceros, Fusion 360 by Autodesk, 3Ds Max, Blender) by utilizing the tools to build cures and surfaces. The other method is substantially advanced computational designs (e.g., Grasshopper, Dynamo, and Python). This type of 3D modeling process can achieve design efficiency and complexity through parametric or generative methods, for instance, the lattice structures. In finalizing the design for the 3DP process, digital files in.stl format are often perfected for accuracy before printing in 3D CAD programs, such as Netfabb and Meshmixer.

At present, adaptation to new technologies in the fashion industry is inevitable. Traditional fashion design training and problem-solving are based on hands-on skills in flat pattern-making, draping, and sewing techniques. Several CAD integrations, such as digital textile design and knitting, are mostly considered as 2D digital design, unlike the 3D CAD in 3DP. Visual intelligence, such as manipulating objects' spatial visualization skills, is somewhat foreign to typical fashion designers (Sun & Zhao, 2017). To effectively evaluate wearable fashion products, such as garments in a 3D virtual space, advancements to integrate traditional skills (e.g., draping)—in combinations with new materials (e.g., filament vs. resin) and traditional fabrics—into the processes of 3DP fabrication is imperative.

Innovations and Interdisciplinary Thinking in 3D Printed Fashion

Considering the growth in the fashion industry over the past two decades, fashion professionals have recognized the potential in 3DP and expressed their fascination toward possible innovation resulting from interdisciplinary designs (Delamore, 2004; Sisson & Thompson, 2012; Sun & Zhao, 2017). Considering the impact of 3DP in the fashion industry, fashion designers no longer only speculate regarding the product's visual qualities but, in several cases, also have to deal with the whole supply chain, design, manufacturing, and retail (Sun & Zhao, 2017). Therefore, in a technology-driven fashion network, designers now undertake more demanding roles (Sun & Zhao, 2018) to work closely with professionals from other fields, such as computer science, industrial and architectural design, and even biological and material engineering to effectively solve critical problems they encounter and maximize the value of 3DP in fashion. Therefore, modern designers, makers, and users in fashion with a divergent and well-rounded knowledge base have become essential (Sun & Zhao, 2018). The following case studies represent different 3D printed fashion product categories and interdisciplinary knowledge bases required for innovation. Further, they entail the nuances of 3DP in product designs, hacking in technology and material, and their current values in diverse market environments.

Case 1: 3D Printed Footwear in Mass and Limited Manufacturing

In the development of 3D printed footwear, the production of shoe soles has been a major application (Jin & Cedrola, 2018a). After successfully launching its first 3D printed sneaker in 2017, Adidas has since attracted significant market demand and interest. Therefore, it has a solidified position in manufacturing 3D printed footwear and helps catalyze the next level of advancement for 3D printed fashion. The design focuses on the midsole that is manufactured by the means of the Digital Light Synthesis™ technology by Carbon, a type of DLP 3DP method that fabricates with UV-curable resin and TPU mixture (Adidas, 2019). Their uniqueness resides in the adaptable lattice structure of the midsole. The structure not only creates visually appealing footwear but also intends to adapt to the wearer's movements. Adidas emphasizes that the technology records data to translate the user's performance needs for personalized cushioning and stability in the midsole (Adidas, 2019). Its FW 2019 version, AlphaEDGE 4D, features a reflective knit upper for the purpose of training in low light (Adidas, 2019).

After the initial launch of its 3D printed footwear in 2017, Adidas produced only 5,000 pairs (McKenna, 2017). By the end of 2018, manufacturing scaled up to 100,000 pairs and continued to rise as the brand introduced more variations (Cheng, 2018). Having accomplished remarkable success, the 3D printed footwear line includes neutral color combinations, shoe upper material mixtures, gender-based style selections, and even design collaborations with Stella McCartney (Boissonneault, 2019). Most of its styles are currently available through popular global retailers at the price of 300 US dollars. Logistically speaking, Adidas reduced the lead time in 3DP manufacturing and managed their global supply chain efficiently. It recently closed two of its Speed Factory facilities, initially developed for faster delivery in the West, and is moving into Asia to expand its 3DP operations to allow itself greater flexibility in working with its suppliers (Goulding, 2019).

In terms of expanding the frontiers in the development of economical and adaptable 3D printed footwear, Nike's latest invention focuses on developing the 3DP shoe topper by implementing the FDM method. Although Nike has a long history of using 3DP, it has been mainly applied for prototyping and shoe plate developments. Nike's Vaporfly Flyprint sneaker is the world's first performance footwear with a 3D printed upper (Nike, 2018). It was initially designed for marathon runners by applying the FDM 3DP technology with TPU filament, to achieve the lightest weight footwear with a highly breathable quality for running activities. Color variations were achieved by fusing different layers of 3DP filaments for an interwoven mesh look. The advantage of the 3D printed mesh pattern is that it has fused intersections that provide significant potential for precise engineering in pressure and supporting the runner (Nike, 2018). The tongue is fabricated by implementing Nike's Flyknit technology with traditional textiles, which is seamlessly heat-fused with the 3D printed portion at the edges.

In the application of the FDM 3DP technology for shoe upper, developing Vaporfly Flyprint only consumed approximately half of the expected time that is spent in the production of a traditional sneaker. Essentially, the use of 3D CAD and less complicated printing technology enable the design team to quickly and effectively execute adjustments, establish variations for testing, and accomplish design finalization. It currently has two color options with limited production at the retail price of 600 US dollars. Flyprint is essentially a peek into the future with more advanced 3D printed performance footwear. Further sophisticated modifications are expected for the general market with a lower price range in the near future.

Case 2: 3D Printed Apparel in Ready-to-Wear and Customization

In the world of ready-to-wear 3D printed apparel, the Israeli fashion designer, Danit Peleg, has played an instrumental role. In 2015, she debuted the world's first completely 3D printed ready-to-wear apparel collection. Her work has since evolved into a 3DP business of customized apparel and fashion training. In her designs, she relies on FDM 3DP and mostly develops 2D flexible and wearable 3D printed textiles. In her 3D Printing Fashion Studio, Peleg debuted the collection titled The Birth of Venus (Danit Peleg, 2018). It features a versatile and customizable jacket that can be personalized with 3D printed colors, silk lining colors, text, and preset sizing with an option to confirm measurements that employs a mobile body scanning app, Neitelo, for the purpose. This jacket is a front zip-up and fabricated from a sourced textile pattern capable of producing a unique and beautiful drape. In 3D CAD, the pattern was 3D modeled by utilizing the common direct modeling technique that, in this case, enables numerous zigzag units to conjoin together to fabricate a large sheet of four-way stretch 3D printed textiles. The textile was later cut and assembled with other garment parts, such as cuff, zipper, and silk lining. Peleg mainly relies on a commercial-grade FDM 3D printer that produces Filaflex 3DP filaments, a kind of TPU material with a rubbery hand. This jacket requires more than 100 hours of printing and assembly time and is retailed at 1,500 US dollars.

Today, Peleg understands the importance of promoting 3DP by educating consumers on the value and potential of 3D printed fashion and aims to empower the average fashion consumer with the basic skills in exploring this technology with the growing prevalence of home 3D printing. Since 2018, she has been conducting both in-person workshops and online courses that quickly gained popularity and is forming an impactful 3DP fashion community. In further advancing the capability of 3DP in the field of fashion, Peleg has also collaborated with the digital garment-making technology giant, Gerber, to explore more efficient software and automation solutions for modern designers (Gerber Technology, 2016).

For ready-to-wear 3D printed apparel, Julia Daviy (https://juliadaviy.com/) is another unique award-winning brand, targeting the woman's cocktail apparel and handbag market. Like Danite Peleg's collections, Daviy focuses on creating 3D printed textiles in her wearable apparel. Her 3D CAD process applies the direct 3D modeling technique, developing a 2D repeating pattern, which she also 3D printed in large sheets by the means of the FDM technology with TPU filaments. She believes that her 3D printed textiles provide the touch and the texture that can serve as a unique alternative to traditional leather materials (Daviy, 2019).

Daviy has so far, both partially and completely, explored 3D printed garment pieces utilizing both standard and advanced 3D modeling approaches. Her Coral Pleated Dress applied the parametric 3D modeling method, a computational design technique, to accomplish the development of organic pleats that hug the body and accentuate the curves. The vertically shaped pleats were 3D printed using TPU filaments and were later assembled with conventionally woven textiles. In her customizable product, she focused on the classic skirt styles, including pencil, mini, and A-line silhouettes. Consumers can customize waistline height, pocket, and preset colors and sizes, selecting from over 270 design variants. The skirt designs were lined with traditional textiles and featured a symmetrical organic pattern that generates a lace-like effect. After each skirt piece was 3D printed over the span of 12–20 hours, each piece was assembled through a gluing technique. Like Peleg's jacket, Daviy's skirt also provides an online virtual simulation tool to allow for 360-degree viewing of the chosen product. Daviy's skirt currently retails at 780–1,500 US dollars.

Case 3: 3D Printed Computational Design for Customization, Made-to-Order Production, and Consumer Engagement

In the world of 3D printed fashion e-Commerce, the leading marketplace, Shapeways, has been instrumental in connecting the industry to the average consumers at home (Everett, 2021). It is a 2007 Dutch-founded company, presently, a New York-based company that provides a platform for 3DP online shop owners and an inclusive on-demand 3DP service for entrepreneurs, designers, and enthusiasts. Over the years, Shapeways has transformed into a place that supports and nurtures a vital 3DP community. Equipped with industrial-grade machines, its production location in Long Island City, NY, is currently one of the world's largest additive manufacturing facilities. By collaborating and co-branding with the global chemical producer BASE, it aims to make high-performance materials more accessible to consumers and leverage additive manufacturing services for the global 3DP network.

In its developing stages, the company focused mainly on stores that sold custom-made fashion products, such as jewelry, wearables, creative figuring, and decorative sculptures. One of them includes the 3D printed fashion pioneer, Continuum Fashion by Mary Huang, a media artist (Continuum Fashion, n.d.). It acquires a line of jewelry, and the company is well-known for N12 Bikini in selling them individually. This highly wearable and innovative bikini design was intended to be fabricated with nylon utilizing the SLS 3DP technology. In collaboration with the architect Jeena Fizel, it was designed through computational modeling techniques in the 3D CAD process to achieve a circular packing system that provides flexibility in the 3DP textile and unique aesthetics for the design (Continuum Fashion, n.d.). Selling separate parts of the bikini in various preset sizes and two basic colors, this store essentially allows the consumer to further customize the bikini with alternative straps or other notions.

In developing advanced 3D CAD technologies for fashion, Nervous System is perceived as the leading company (Nervous System, n.d.). It is a studio founded to focus on generative design technology, a type of computational design that often relies on software to generate several CAD-ready designs simultaneously. The studio's most well-known creation, Kinematics Dress, features not only one of the first articulating 3D printed garments with interlocking components but also advanced

3D CAD design and simulation applications (Nervous System, 2014). The Kinematics can auto-generate the tessellated structure for apparel or jewelry design. Presently, the studio develops upon previous technologies and aims to enrich the consumers' online shopping experience through its various web-based software for jewelry customization. In its user-friendly design centers, consumers can virtually design their own jewelry pieces with simple presetting selections in a matter of minutes. The shop currently offers materials ranging from popular plastic options to wood and metals with jewelry products, ranging between 30 and 100 US dollars.

Conclusion and Future Trends

Through the perspective of DDM and a technology-driven fashion network (Sun & Zhao, 2018), this chapter discussed the advantages and challenges in 3DP technologies, materials, and 3D CAD in 3DP fashion. It focused on presenting three practical interdisciplinary case studies that revealed the technology applications of 3DP in different fashion product categories for the modern market. Three case studies of 3DP fashion products are summarized in Fig. 4.1.

In terms of innovating 3DP fashion products, several critical guidelines should be considered: (a) selecting 3DP methods and materials based on the wearability of the intended fashion product's functions and aesthetics, (b) the feasibility in final construction or assembly, (c) the level of complexity in post-finishing techniques, and (d) the practicality and novelty in product end-use. Considering market feasibility, additional considerations are required to emphasize the most valuable aspect of the 3DP product and the product yield, production complexity and speed, and inventory and distribution approaches.

For the future, as the technology of 3DP advances, the following key areas should be emphasized to adapt, adopt, and maximize the advantage of additive manufacturing and DDM technologies for the modern, digital fashion supply chain.

- Novel 3D CAD techniques for unique product development needs: Parametric and generative 3D CAD are essential skills in enhancing the sustainability of the 3DP product development process and the workflow for fashion products.

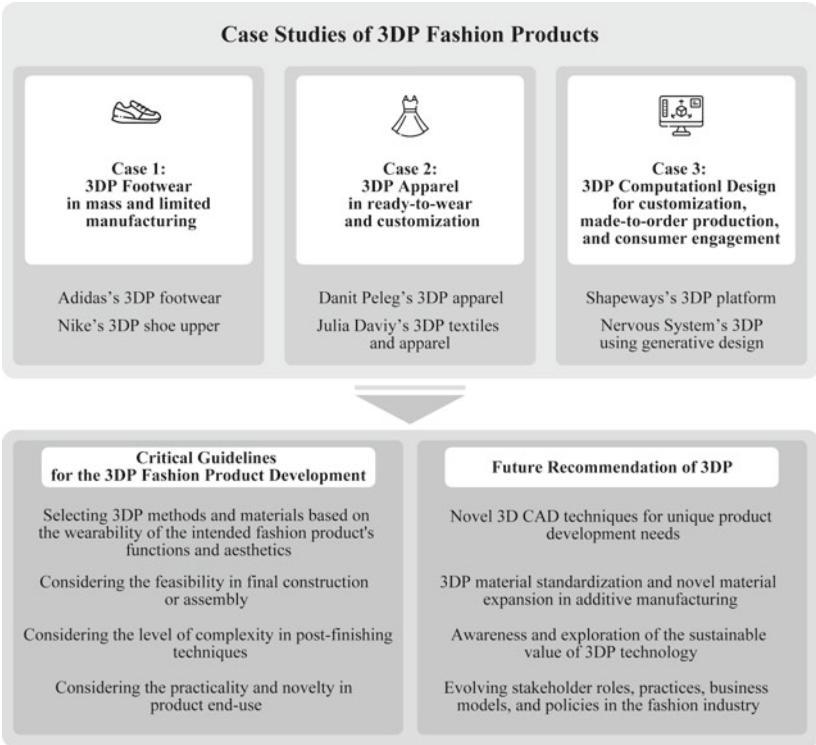

Fig. 4.1 Summary of Cases Studies of 3DP Fashion Products (*Source* Developed by the book editor)

- 3DP material standardization and novel material expansion in additive manufacturing: Current 3DP material has existing property references only at the polymer level, not at the final structural level, which can be complex. Standardization in the materials' structural evaluation requires progress to support the efficient 3DP product development process. Bio-based polymers and materials that optimize environmentally sustainable qualities will become more valuable for exploration and integration in various 3DP technology hackings in material composition.
- Awareness and exploration of the sustainable value of the 3DP technology: As additive manufacturing and DDM technologies expand,

the fashion industry is yet to establish critical links to sync all the sectors sustainably. Therefore, the industry and consumer education, talent incubation, and the industry's technical support must prioritize establishing a solid foundation for future developments.

- Evolving stakeholder roles, practices, business models, and policies in the fashion industry: As collaboration and co-design become inevitable and invaluable as ever in the digital era, in-depth investigations must be conducted to solve critical problems and support the overall vitality and transition of the fashion industry.

Sources of Further Information

For additional information regarding technology innovation in 3DP fashion products, please reference the following collection of resources.

- Danie Peleg (https://danitpeleg.com/): A fashion designer and pioneer in 3D printed fashion.
- Julia Daviy (https://juliadaviy.com/): A designer who pioneered the usage of digital 3D design and additive manufacturing for the sustainability of clothing, bags, and accessories.
- Nervous System (https://n-e-r-v-o-u-s.com/): A generative design studio that works at the interaction of science, art, and technology using 3D printing technology. They create computer simulations to generate designs and use digital fabrication to realize products.
- Shapeways (https://www.shapeways.com/): A platform for 3DP online shop owners and an inclusive on-demand 3DP service for entrepreneurs, designers, and enthusiasts.

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