NC STATE
Wilson College of Textiles

JTATM
Journal of Textile and Apparel, Technology and Management

Volume 11, Issue 3, 2020

A Critical Review of Additive Manufacturing: An Innovation of Mass Customization

Yanan Yu, Gwia Kim, Dr. Kavita Mathur,
Textile and Apparel, Technology and Management,
Wilson College of Textiles,
North Carolina State University

ABSTRACT

Purpose
This paper reviews the literature on state-of-the-art 3D and 4D printing technology in the fashion mass customization context and proposes an innovative design concept for improving independent designers' and small and medium enterprises' (SMEs) practice, premised on commercialized technology and accessible materials in the fashion mass customization business.

Design/methodology/approach
The literature review of 3D and 4D printing technologies enabled discussion of the possibilities of using them for mass customization, especially in the fashion industry. Then the study presented a prototype suggesting an approach to improve mass customization by combining two technologies.

Findings
The intrinsic worth of 3D and 4D printing technology has inspired researchers to strike an innovative path towards exploiting the potential for mass customization in the fashion industry, through embedding shape memory materials into 3D-printed objects. 4D printing was confirmed as offering potential for application in the fashion industry.

Research limitations
A fashion accessory case was presented, exemplifying such 3D/4D printed fashion items, but more studies experimenting with other types of fashion products are warranted.

Originality/value
This paper establishes appropriate knowledge flows between 4D printing technology and its commercial possibilities, by identifying the strengths of 4D printing technology, particularly in the fashion industry. In addition, integration of 3D and 4D printing components is proposed, to reduce consumer return rate and increase products' hedonic value by facilitating change of shape of the 3D-printed object post printing.

Keywords: 3D printing technology, 4D printing technology, shape memory composites, mass customization, fashion accessories

1. Introduction

The requirement of manufacturing fashion and apparel products based on individual consumers' varying demands has prompted the apparel industry to undergo a fundamental shift from mass production to mass customization (Senanayake & Little, 2010). A YouGov survey in 2018 found that 29% of U.S. consumers have personalized a fashion product and are willing to pay a premium for custom apparel and footwear (Garcia, 2018). It is expected that the market for mass customization of garments will touch 27.2 billion euro in 2020, corresponding to 5% of the global fashion market (Probst et al., 2013).

3D printing, an automated additive manufacturing technology that prints by adding successive layers using a polymeric material in order to create an object (Cuzella, 2015; Mellor Hao, & Zhang, 2014), has been utilized in mass customization. This technology has proved its potential to resolve one of the issues of mass customization, that is the conflict between efficiency and flexibility in mass manufacturing (Berman, 2012; Michalik, Joyce, Barney, & McCune, 2015). 3D printing technology expands mass customization manufacturing, because it enables small quantities of customized items with low unit price to be quickly and easily modified based on computer aided design (CAD) software (Berman, 2012; Michalik et al., 2015).

Nevertheless, the current capabilities of 3D printing have not fully met mass customization requirements, as the energy consumption and labor cost incurred after the objects have been printed is not considered in the entire process (Tibbits, 2014). 4D printing seems to have overcome this obstacle, emerging and gaining considerable traction recently with its three components; the smart material, the geometric program, and the multi-material printer (Tibbits, 2014). Unlike 3D printing, 4D printing technology envisages independent shape transformation, when encountering a stimulus after the objects have been printed. This function is also known as "self-assembling", "self-reconfiguring", and "self-adaptability" (Tibbits, 2014; Momeni, M.Mehdi Hassani.N, Liu, & Ni, 2017). However, despite the importance of mass customization and the great potential of 3D and 4D printing technology in mass customization, there is limited literature available that addresses recent advances in this area.

This study, therefore, aims to review the current advances in 3D and 4D printing in order to explore the practicability of mass customization. Unfortunately, 4D printing has not yet been adopted on an industrial scale, due to lack of commercialized multi-material printers (Headrick, 2015). In light of this situation, the current study has three objectives: 1) to review the characteristics, applications, advantages, and shortcomings of 3D printing, particularly in the mass-customization environment of the fashion industry, and the emergence of 4D printing; 2) to establish appropriate knowledge flows of 4D printing technology and its commercial possibilities by identifying the strengths of 4D printing technology; 3) to propose, based on the literature, a creative design approach to the mass customization business in the fashion industry premised on the commercialized technology and accessible materials, for independent designers and small and medium-sized enterprises (SMEs).

2. Literature review

2.1 Current use of 3D printing in the fashion industry

3D printing technology relies on digital models, materials, and machines, as depicted in Figure 1. As shown, 3D printing involves a digital model to be printed, so designers commonly use CAD modeling software or online 3D printing platforms that offer design capabilities (Rayna & Striukova, 2016). Designers can also use 3D scanning to create a digital model (Gibson, 2017; Rayna & Striukova, 2016). According to Vanderploeg, Lee, and Mamp (2017), the design and division process of layers is performed through 3D modeling software. Accordingly, modification in measurements, design components, or adjustments can be done between the process of designing and division or layers. Thus, it offers designers and engineers the flexibility to design and test prototypes as many times as needed. 3D printing technology has seen widespread adoption in many industries, and of late the apparel and fashion industry has also accepted this technology to develop prototypes, customizable products, and haute couture products (Vanderploeg et al., 2017). However, specific materials and methods are needed for wearable applications.

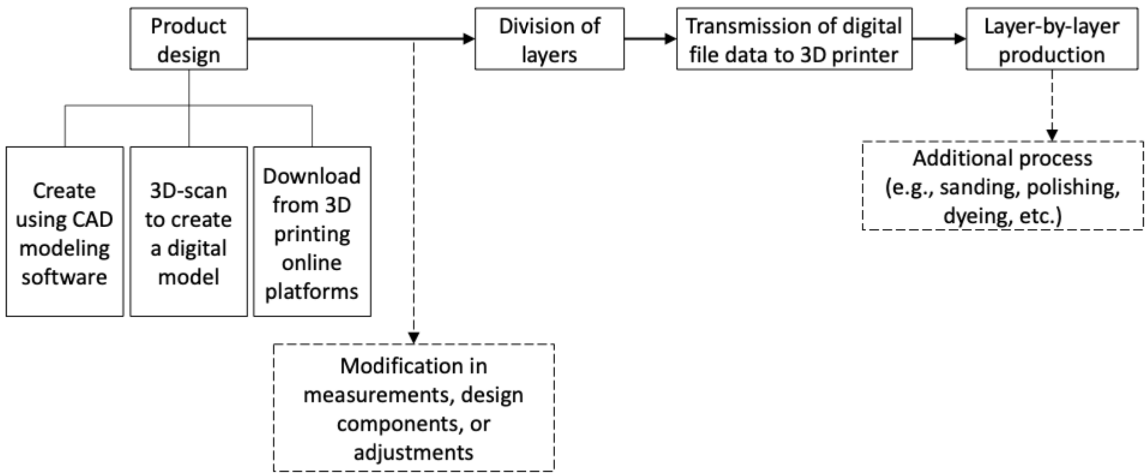


Figure 1. General 3D printing design and process
Source: Developed by the authors based on literature

The most commonly available 3D printing materials include: glass, ceramics, metals, polymers, and resins, and for the fashion products, natural and synthetic fibers or filaments (e.g., cotton, nylon, polymers, and leathers) (Cuzella, 2015). However, many of these materials are not flexible or are uncomfortable. For example, a textile company, Continuum, offered a customizable 3D-printed bikini using a nylon plastic filament (Continuum, n.d.). Although they were able to achieve the required shape and size, the material lacked flexibility. In recent years, the fashion industry has been working on developing a new filament to achieve more applications of 3D printed products. One company, TamiCare, has developed a 3D printing technology called Cosyflex (TamiCare, n.d.). This enables printing fabrics using liquid polymers such as natural latex, polyurethane, and Teflon, and textile fibers such as cotton, rayon, and polyamide (Yap & Yeong, 2014). Furthermore, sportswear retailer Nike has introduced Flyprint, which is the first 3D printed upper material in performance footwear (Bain, 2018). Nike created this product through a solid deposit modeling process. In this process, the thermoplastic filament is loosened from a coil and melted in the 3D printer to be layered. Flyprint is different from traditional 3D printed fabrics, as it is made from a lattice of fused material which imparts flexibility and breathability, and is lightweight. More recently in 2019, Material ConnecXion, a materials consultancy dealing with newly developed 3D printing materials, displayed a polyethylene terephthalate glycol-modified (PET-G) filament in their cutting-edge materials library in High Point, North Carolina. This was developed as a copolymer version of polyester, and has a lower melting temperature than other types of PET. PET-G is prototyped for household goods and jewelry, but has not yet been explored for apparel applications. However, none of these initiatives have been successfully commercialized yet.

The printing method is another important factor that determines the degree of acceptance of 3D printing technology. The available printing methods include: stereolithography (SL), continuous liquid interface production (CLIP), multiphoton polymerization (TPA), selective laser sintering (SLS), fused filament fabrication (FFF, i.e., fused deposition modeling, FDM), etc. (Lulzbot, n.d. ; Vanderploeg et al., 2017). Of these, Vanderploeg et al. (2017) have pointed out that SL, SLS, FFF (i.e., FDM), PolyJet, and binder jetting are the methods that can be applied to fashion products. SL uses a photopolymer resin that is a liquid plastic and an ultra-violet (UV) laser that can strengthen these layers (Huang, Liu, Mokasdar, & Hou, 2013; Vanderploeg et al., 2017). Selective laser sintering (SLS) exploits high-powered lasers to blend minuscule particles of polymer powder so that a 3D printed object can be created, and the process is called sintering (Huang et al., 2013). The designers can create delicate, durable, and highly functional products; therefore, it is suitable for creating high-quality metal jewelry and watches, rather than apparel (Vanderploeg et al., 2017). FFF prints with a liquid thermoplastic filament that is heated to 1 °C above the material's melting point (Vanderploeg et al., 2017). The melted filament then becomes dry and firm almost immediately after layer-by-layer dispersion (Vanderploeg et al., 2017). PolyJet selectively drops beads of liquid photopolymer resin to create an object, and then a roller makes the surface of the layer even (Vanderploeg et al., 2017). In order to harden the liquid resin, two UV lights successively pass over the built layer several times. Binder jetting is also widely used in the fashion industry. It uses glue or binder to bond successive layers of powder material (Bogue, 2013; Hoskins, 2013). As this method can bond single layers within seconds, it is the fastest 3D printing technique (Huang et al., 2013). However, binder jetting can create weaker or uneven surfaced products (Huang et al., 2013). Based on the literature, it is evident that 3D printing has high potential in the fashion industry, but requires some advancements in printing technology to make it adaptable for wearable applications.

2.2. The strengths and weaknesses of 3D printing in mass customization

Mass customization can be a beneficiary of 3D printing technology, particularly in the fashion industry. Mass customization is heavily reliant on a flexible process to produce varied or individually customized products (Hart, 1996). In traditional manufacturing settings, mass customization means smaller batch sizes, specialized high flexibility machinery and equipment, and long production runs, all of which lead to higher costs, longer lead times, and an unstable production process (Lowson, 2001; Schenk & Seelmann-Eggebert, 2003; Zipkin, 2001). Given these obstacles, 3D printing technology has emerged in this field as a means to increase the efficiency and effectiveness of the design process by reducing design constraints and simplifying the process (Michalik et al., 2015). Specifically, the technology enables small quantities of customized items to be produced at a relatively low unit price (Berman, 2012). Since designing and manufacturing can happen virtually anywhere with the 3D systems and printers (Michalik et al., 2015), consumers can be offered a flexible approach to the design process. In addition, companies can create new projects and test prototypes at a quicker pace than before using 3D printing technology (Michalik et al., 2015), prior to final production. For example, Nike uses 3D printing for prototyping, and they have mentioned that it is 16 times faster to make prototypes with 3D compared to any previous manufacturing method (Bain, 2018).

Moreover, 3D printed fashion products can contribute to sustainability. A company named Ministry of Supply has been utilizing 3D printing for knits, and this has helped the company to behave sustainably (Leighton, 2017). The 3D printing process generates almost no waste, compared to traditional manufacturing (Leighton, 2017). Normally, knit production emits 35% leftover fabrics (Leighton, 2017). In addition, 3D printing also limits stock, so that inventories become leaner (Weller, Kleer, & Piller, 2015). In other words, it is possible to produce according to make-to-order processes, so that stocks of unsold items decrease. There are examples of designers who undertake 3D printing to be sustainable. One designer, Julia Daviy, adopted 3D printing when she realized how traditional apparel production itself creates labor-intensive and environmentally irresponsible side effects (Gonzalez, 2019). She 3D-prints activewears, dresses, and tops in an environmentally friendly way because she does not need to mass-produce and stock (Gonzalez, 2019). Another designer, Goldstein, values sustainability in her design, so she developed her own weaving process using Prusa i3 Mk3 3D printer, which is one of the most commercialized 3D printers (Scott, 2018). She has also worked with Stratasys Ltd, an industry leader in multi-material printing, to create a 3D printed pair of shoes through a Connex3 color 3D printer, and she further plans to include recycled plastic as a material (Scott, 2018).

While there are advantages of 3D printing in producing fashion products, there are also some limitations of 3D printing. One of the most significant challenges of 3D printing is the labor and energy cost in manufacturing after the objects have been printed (Tibbits, 2014). Specifically, the majority of current 3D printers cannot print an entire garment within one printing process. For example, Dutch designer Iris Van Herpen exhibited 3D-printed clothing at the 2013 Fashion Week in Paris, and the designer fabricated a dress using thermosetting polymers and tulle to be inserted in the 3D printer (Mendoza, 2018). The dress was not able to be printed in a single pass; instead, it was created in several patches to be sewn together into a single piece of dress. Also, the luxury knitwear fashion brand Pringle of Scotland launched their 2014 Fall/Winter ready-to-wear collection that incorporated 3D printed fabric. In this collection, the designer utilized the selective laser sintering process to produce a more flexible and movable 3D printed textile, which then required workers to stitch them into the wool (Chavez, 2014). Consequently, mass customization cannot ignore the time, labor, and energy needed after the textile has been 3D printed.

Additionally, return issues of the 3D printed customized product remain a challenge in the mass customization business. The size and shape of a 3D printed object cannot change once the object has been printed. Theoretically, customers should be less likely to return a customized product, but inevitably some will. A few retailers accept customized product return (e.g. Nike) (Nike, n.d.), undertaking the financial loss since reselling is not allowed for customized products. Hence, 4D printing has emerged as an innovation of 3D printing technology. With its self-assembling capability, 4D printing has the potential to disrupt 3D printing by reducing the labor and energy costs and enabling consumers to change the customized product's shape or size after it has been printed.

2.3. 4D printing technology

4D printing was initially defined as 3D printing plus an extra dimension—time (Pei, 2014). 4D printing means that the shape, property, or functionality of a 3D printed object can change as a function of time (Momeni et al., 2017; Pei, 2014). Skylar Tibbits (2014), Director of the Self-Assembly Lab at the Massachusetts Institute of Technology (MIT), is one of the first scientists to propose the 4D printing concept. Tibbits worked with Stratasys Ltd to develop 4D printing with the ability to change the shape of 3D printed objects in post-production, when the object confronts a particular stimulus. A 4D printed object is printed just like any 3D printed shape, but this technology enables a 3D-printed object to be programmed to self-assemble.

4D printing is a material science-based technology, which relies heavily on smart materials with the appropriate chemical properties. Invernizzi, Turri, Levi, and Suriano (2018) indicate that one of the most crucial attributes of 4D printing materials is stimuli-responsiveness. Thus, shape memory composites have gained increasing industrial attention. Shape memory composites contain shape memory alloy (SMA), shape memory ceramic (SMC), shape memory gel (SMG), and shape memory polymer (SMP) (Sun et al., 2012). Of these, SMP is particularly popular and has been applied in various industries, such as in biomedicine (Xie, 2011), microelectronic engineering (Gall, Kreiner, Turner, & Hulse, 2004), and also textile science (Hu, Meng, Li, & Ibekwe, 2012) for its high elastic strain (Razzaq, Anhalt, Frormann, & Weidenfeller, 2007), tailorable transition temperature (Miaudet et al., 2007), and easy production and operation (Santo, Tedde, & Quadrini, 2015).

SMPs are "polymeric smart materials that have the ability to fix a deformed state (temporary shape) and to recover back to their original states (permanent shapes) upon the application of certain external stimuli" (He, Guo, Liu. & Liew, 2015). Prior studies classify SMPs into different categories according to the stimuli. For example, Leng, Lu, Liu, Huang, and Du (2009) categorized SMPs into thermo-responsive SMPs, chemo-responsive SMPs, and light-responsive SMPs. The thermal sensitive SMP enables shape recovery when a temperature change is triggered, which is the thermally induced shape memory effect. The heating in the thermo-responsive SMPs can be in various ways, such as inductive heating, joule heating, light heating, and ultrasonic/acoustic heating (Huang et al., 2012). The shape recovery of chemo-responsive SMPs occurs upon their immersion into a special liquid chemical, when solvent molecules diffuse into the polymer and act as a plasticizer (Leng et al., 2009). Additionally, light-responsive stimulation of SMPs, which has been realized through the incorporation of reversible photoreactive molecular switches (Leng et al., 2009), is classified into two types: the intrinsically light-induced SMP, which is only sensitive to certain wavelengths of light and is independent of the temperature effect; and the indirect thermal actuation SMPs, which can effectively absorb infrared light and heat to actuate the structure to recover its original shape (Liu, Du, Liu, & Leng, 2014).

However, not all stimulus-responsive components can undergo an intended transformation when only exposed to an optimum stimulus. A set interaction mechanism is necessary to plan out the sequence of shape-shifting behaviors when triggered by the stimulus for an appropriate period of time (Pei & Loh, 2018). This leads to another key component for 4D printing viability—the design of the geometric program. Tibbits (2014) states that the design and placement of the geometric program embed the capability for state change directly into the materials themselves. Thus, the interaction mechanism of 4D printing is to combine smart materials with a sophisticated design of the geometric program.

Tibbits (2014) conducted an experiment using a hydrophilic polymer that expands 150 percent when it encounters water. This dynamic and rigid material was developed by giving the structure and angle limiters for folding. The water is the plasticizer in this experiment which forces the rigid material to bend. When the rigid material reaches the angle limiter, it stops folding. Moreover, Raviv et al. (2014) indicate that in the 4D printing process, multiple materials usually need to be inserted into a single structure or single layers are combined to yield multi-layer structures to develop different density at various locations. In order to perform shape-shifting behavior, there are at least two stable states in a 4D printed structure. Momeni et al. (2017) summarize the shape-shifting behaviors considered in 4D printing as including folding, bending, twisting, linear or nonlinear expansion/contraction, curling, wrinkling, and creasing. The structures that show 1D to 1D, 1D to 2D, 2D to 2D, 1D to 3D, 2D to 3D, and 3D to 3D shape shifting over time are all considered as 4D printed structures. Additionally, based on the previous studies (e.g., Ge, Qi, & Dunn, 2013; Ge et al., 2016; Momeni et al., 2017; Tibbits, McKnelly, Olguin, Dikovsky, &, Hirsch, 2014), 4D-printed multi-material geometric structures have been categorized into three patterns: uniform distribution with different concentration, gradient distribution structure, and special patterns. In general, various geometric structures can be created with multi-material distributions in an optimal way, enabling different shape-shifting performance.

4D printing focuses on the multi-material structure, and the desired properties have to be compatible with printers. Thus, 4D printing entails a 3D printer which is able to print multi-material structures. To distinguish this specific 3D printer from a traditional 3D printer, it is also known as a multi-material printer. In Tibbit's experiment (2014), Stratasys's Connex machine that offered multi-material PolyJet printing was utilized, which enabled shape-transformation from one state to another, directly off the print-bed. However, compared to a conventional 3D printer, multi-material printers are yet to be commercialized. Thus, although 4D printing has lent itself to countless innovations, that does not mean they are easy to achieve. Fortunately, many researchers and organizations are working on developing multi-material printers. Apart from Stratasys Ltd, Singapore University of Technology and Design is publishing a project of making a new **digital light processing** (DLP) 3D printer that uses multiple materials to make quality components (Kowsari, Akbari, Wang, Fang, & Ge, 2018). Therefore, although the majority of 4D printing projects remain in the laboratory development stage (Pei, 2014), the time is ripe to establish appropriate knowledge flows between 4D printing technology and its commercialization possibilities. The rest of the paper presents the strengths and potential applications based on a literature review of 4D printing technology in the fashion industry.

2.4. The potential of 4D printing for mass customization

Grounded in the characteristics of 4D printing technology, this study critically analyzes 4D technology for better mass customization. This technology contains most of the advantages of 3D printing, but further promotes the development of mass customization with regard to manufacturing, sustainability, inventory and transportation, and comfort. Figure 2 summarizes mass customization applicability using 4D printing technology, based on the literature review undertaken in this paper. Moreover, Figure 2 illustrates the conceptual framework of the design concept we proposed in Section 3 by integrating existing 3D printing components and one of the significant 4D printing components, i.e. stimuli-responsive materials. The proposed conceptual model suggests how to complete the shape changing in the post-production process, which in turn, reached a certain degree of 4D printing potentials without the investment in multi-material printer.

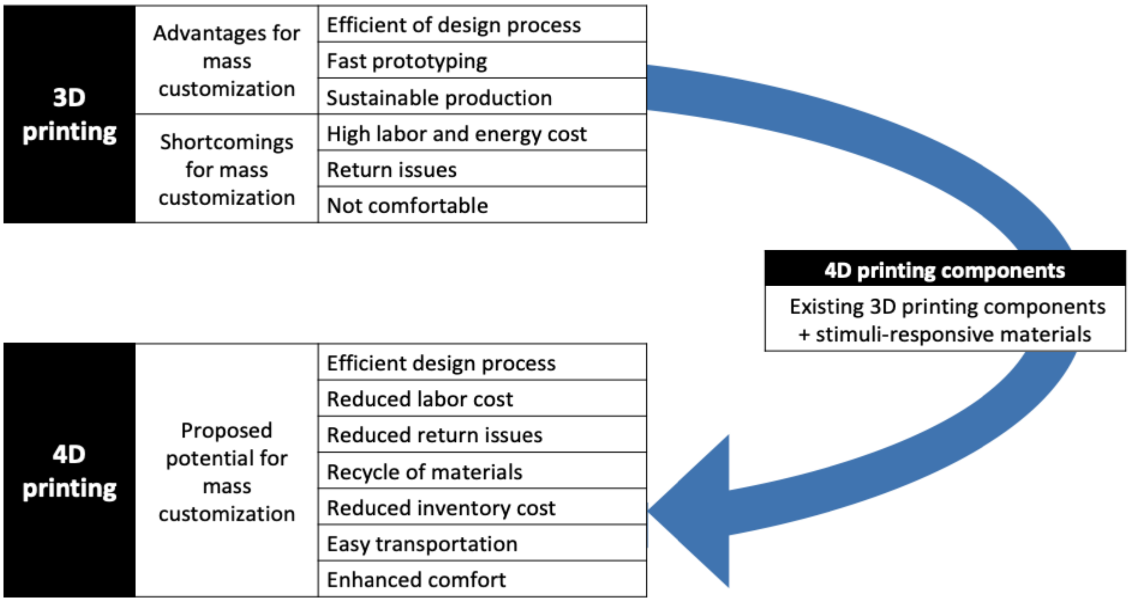


Figure 2. A proposed potential of 4D printing technology for mass customization (MC) through 3D printing advantages and 4D printing components.
Source: Developed by the authors based on literature.

4D printing is a revolution in manufacturing by reducing time and labor cost for assembly (Tibbits, 2014). The high labor cost in developed countries forces the majority of fashion brands to engage contractors in developing countries to reduce labor cost. Nevertheless, outsourcing is not a perfect business strategy. For example, the monthly minimum wage in some parts of China has reached $321 in 2016, 15.7% higher than in 2015 (Lu, 2016). It is evident that the predictably growing labor cost in developing countries will account for a growing percentage of the wholesale prices and become an increasingly heavy burden for fashion brands that outsource the manufacturing to contractors. Second, outsourcing increases the risk of having to manage supply chains. According to Jacobs and Singhal (2017), Rana Plaza, an eight-story commercial building that housed 5000 garment factory workers, collapsed in 2013, and this Rana Plaza tragedy resulted from outsourcing to a certain extent. The workers in Rana Plaza worked for Western fashion retailers, but it was difficult for the retailers to monitor the working conditions. The tragedy not only caused financial loss but also hurt the reputation of Western fashion companies (Jacobs & Singhal, 2017). 3D printing only enables production of relatively small custom parts and relies on workers to put them together after the objects have been printed (Tibbits, 2014). The self-assembly capability of 4D printing allows fashion brands to bring the manufacturing back to their place of operation and closer to the markets.

The idea of self-assembly also shows tremendous advantages with regard to sustainability. Tibbits (2014) presented that 4D printing has endless possibilities, considering the reduce, reuse, and recycling qualities of smart materials and designs. If a product can self-assemble then it should also be able to self-disassemble, which leads to easier after-use disposal of the object. Simultaneously, Sun, Huang, Lu, Wang, and Zhang (2014) conducted several experiments to examine the possible approaches to implement shape memory alloy and shape memory polymers' self-assembly and self-disassembly activities. The researchers identified the advantages of using shape memory technology over conventional assembly/disassembly techniques involving physical handling. Due to their special characteristics, the 4D printed objects will not just be thrown away. Rather, they can be self-disassembled for recyclability and reconstitution, which also means less handling and transportation. Hence, 4D printing has a huge potential to reduce fossil fuel usage in fabric and package manufacturing, thereby contributing to maintaining a sustainable environment.

Furthermore, 4D printing technology reduces inventory cost and makes transportation easier. For example, many brands purchase fabric ahead of time and keep them in the inventory to be used for future garment manufacturing, and therefore they require large warehousing space. 4D printing enables the material to remain as 1D strand or 2D sheet preform before application of stimuli, and thus, it saves storage space and reduces the warehousing cost (Choi, Kwon, Jo, Lee, & Moon, 2015). Additionally, compared to the 3D printed objects, 4D printed objects could easily fit into smaller vehicles to be later transformed into real 3D products, which in turn will reduce the transportation cost. In general, 4D printing technology has the ability to enhance the efficiency of the entire supply chain by decreasing labor, inventory, and transportation costs.

Compared to 3D printing, the geometric structure of 4D printing is capable of enhancing comfort attributes, which could not be achieved earlier because of the lack of appropriate materials. Oltuski (2017) indicated that 3D printing could not be widely adopted in the fashion industry because it is not easy to find a printable filament that is flexible enough to make wearable clothing. Indeed, many materials being used in the fashion industry were utilized to produced hard accessories and jewelry rather than apparel products and were applied for creative designs rather than ready-to-wear products (Mendoza, 2018; Vanderploeg et al., 2017). However, many researchers are currently working to create an effective system to turn a 3D printed object into a flexible structure, applying 4D printing materials. For example, Kinematics is a system for 4D printing that creates complex, foldable structures composed of articulated modules (Mok, 2015). Using the Kinematics system, a design studio called Nervous System developed a 4D printed dress that is composed of thousands of unique interlocking components, and the dress responds to the wearer's body.

Nevertheless, the examples of 4D printed garments in the fashion industry are limited. Instead of a head-to-toe garment, the majority of researchers start from fashion accessories, such as rings and shoes. For example, Zarek et al. (2016) produced a set of one-way processed temperature-responsive 4D printed rings that ‘bloom’ when exposed to heat and a 4D printed shoe-heel that changes from high to flat heel. To achieve the shape changing attribute, the researchers established optimal printing conditions and ink compositions by considering the effect of molecular weight on the thermal properties, and the influence of dyes. Moreover, Adidas collaborating with Carbon Inc. released their first collaborative effort: the *Futurecraft 4D* sneaker (Flower, 2017). This sneaker used 4D printed midsoles constructed from a single piece of elastomer that was printed with essentially zero support material. This technology dramatically reduces manual steps after the objects have been printed (Carbon, n.d.). Technically, the capability of customization can be enhanced by 4D printing technology, because 4D printing proposes a new production model to satisfy various design requirements, through shape memory and changing properties.

3. A design concept for small to medium enterprises and independent designers

3.1. Background of an alternative concept: Combination of 3D and 4D printing

The shape-changing property of 4D printing after the objects have been printed shows great potential to disrupt the traditional co-design processes in mass customization. Lampel and Mintzberg (1996) developed a continuum of strategies model which depicts four points of customization: design, fabrication, assembly, and distribution. In the early stage, consumers are involved for customization. Thus, consumers' valuation of the customized product is likely to be higher if they engage in the design stage (Merle, Chandon, Roux, & Alizon, 2010). Normally, consumers' co-design is only allowed in the pre-production stage, and the product cannot be revised after it has been produced or printed. With the self-assembly capability of 4D printing, the shape of a 4D printed object can change independently when a stimulus is applied to it, so that consumers are allowed to adjust the size or shape even after the objects have been printed, according to personal preferences.

Although 3D and 4D printing technologies have been applied in the fashion industry, they have not been widely used because of their inherent limitations (i.e., labor and energy cost of 3D printing, lack of 4D multi-material printers). In particular, SMEs and independent designers who normally have limited budgets and techniques may find it difficult to gain access to the 4D printing technology, as it requires specialized costly multi-material printers, which are not yet commercially available (Headrick, 2015).

Accordingly, the current paper proposes an innovative design idea to combine these two technologies. This section thus aims to develop an innovative approach for the mass customization business in the fashion accessory industry, premised on commercialized technology and accessible materials, considering independent designers and SMEs. By integrating 3D printing technology and a key component of 4D printing, i.e., shape memory material, the product's shape can change independently; moreover, consumers can be involved in design after the objects have been printed.

3.2. An example of an innovative design concept for a fashion product

This experimental work was conducted as a part of a course project at North Carolina State University. In this project, an earring prototype was developed using a Lulzbot Mini 3D printer and polylactic acid (PLA) for a 3D printed pendant, and a heat responsive shape memory alloy (SMA). A printer with FDM technology was used. Although this technology is capable of exploiting soft materials such as acrylonitrile butadiene styrene (ABS) and PLA to print flexible, glossy, lace-like objects (Hoskins, 2013; Melnikova, Ehrmann, & Finsterbusch, 2014), the experiments utilized standard material for prototyping.

The process of creating accessory prototypes includes four steps. Since we aimed to explore an innovative design approach instead of developing a particular design, the following steps were implemented. First, we downloaded the earring pendant file from Thingiverse (https://www.thingiverse.com/), which is licensed for use under creative commons. Second, a user-friendly 3D printing software Cura, maintained by Ultimaker Inc. (https://ultimaker.com), was exploited to process the 3D file. Third, the earring pendant was 3D-printed by the Lulzbot Mini 3D printer using PLA as the filament. Lastly, we combined the pendant and the earring chain constructed from a pre-trained straight shape SMA. The SMA, obtained from an e-commerce site for this experiment, starts becoming rigid and returns to being straight when exposed to temperatures above 104°F. The intensity of the deformation can be controlled by manipulating the temperature; thus, the SMA can be customized into different shapes according to the designers' needs.

Table 1 and Table 2 exhibit the original and stimulated earring prototypes. The original hybrid earring prototype had a five-centimeter-long SMA chain. Thereafter, water at a temperature of 104 °F was used to stimulate the earring chain, which elongated into six centimeters. Next, we exposed the chain to a candle flame, since that is easily accessible to end-users. The chain became fully straight, reaching approximately 10 centimeters. This approach enables creating customizable products to meet consumers' preferences, after the object has been printed. In this process, we found that the more twisted the SMA was, the higher the temperature needed to trigger the deformation. Thus, the customized product can both achieve complex shapes as well as change shape independently in the post-production process without the need to invest in a multi-material printer.

Table 1. The process of the earring prototype length changing

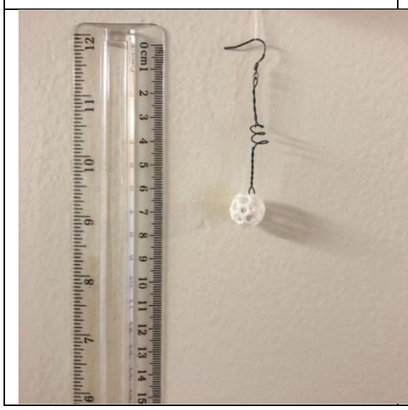
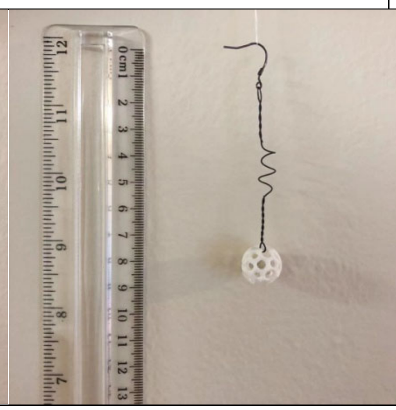
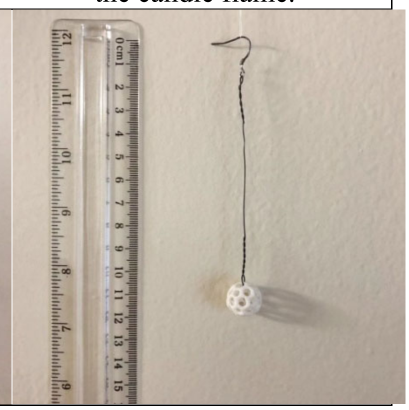
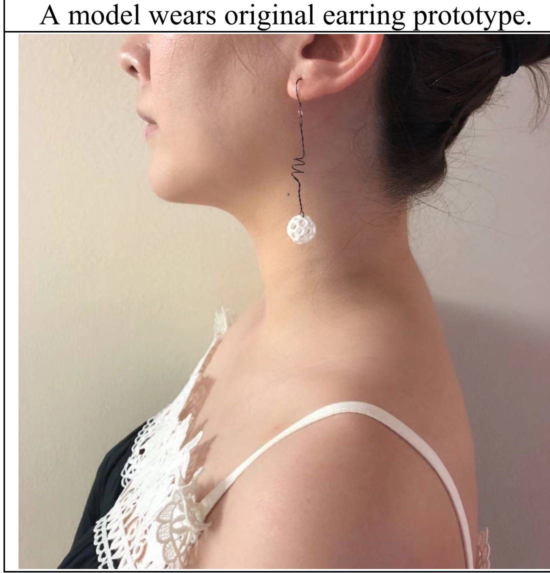
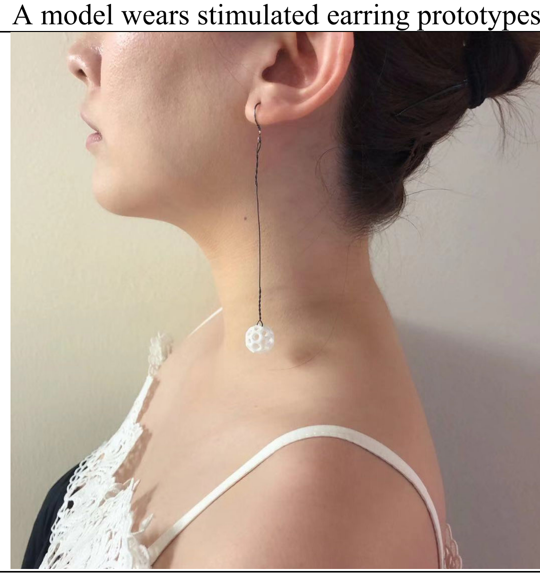
The original hybrid earring prototype had a five-centimeter-long SMA chain.	The chain elongated into six centimeters after exposing to 104 °F water.	The chain became fully straight (approximately nine centimeters) after exposed to the candle flame.
		

Table 2. Wearing effect

A model wears original earring prototype.	A model wears stimulated earring prototypes.
	

It was found that the integration of smart materials into 3D printing sets the stage for customization of how designers think about and interact with products when using the material and the stimuli. Depending on the different sizes and properties that designers expect the fashion product to achieve, multiple 3D printing devices and shape memory materials can be applied. Based on the results of this experiment, it is expected that this method can be explored further for future development of potential fashion accessories.

4. Conclusion

This study contributes to understanding 3D and 4D printing technology by reviewing previous literature within the fashion mass customization context. Furthermore, this study suggests to independent designers and SMEs the approach to a new design concept by integrating the components of 3D printing and 4D printing, through showcasing a fashion accessory prototype developed by the authors. Accordingly, this study underlines the possibility that customers can be engaged in customization even after fashion products of their choice have been printed.

Based on the literature review, this paper has generated some implications about 3D and 4D printing technologies. First, from an academic perspective, the study can serve a basis for understanding on managerial practices of 4D manufacturing in the fashion industry. Previous literature that concentrated on additive manufacturing barely addressed the integration of 4D printing, focusing on use of 3D printer and proper 3D printing materials for apparel and fashion products (Vanderploeg et al., 2017; Yap & Yeong, 2014; Zarek et al., 2016). Thus, conclusions of the study, summarized by the proposed conceptual model, filled the research gap.

Second, this paper reviewed the characteristics of the 3D printing and 4D printing technologies from the perspective of mass customization. Previous literature has shown the evidence that 3D printing technology is effective in implementing mass customization to a certain degree and also discusses the limitations of 3D printing in this area. In addition to the consensus, this paper makes one of the early attempts to discuss 4D printing in the fashion mass customization context.

Third, 4D printing is introduced as another method to promote mass customization by upgrading the efficiency of the entire supply chain, including manufacturing and distribution. The technology is also found to enable companies to create more sustainable and comfortable garments due to its advanced geometric programming characteristics. Therefore, this study has identified the commercial potential of 4D printing in the fashion industry.

Fourth, this study presented an idea for SMEs and independent designers to implement additive manufacturing for mass customization premised on the commercialized technology and accessible materials. Mass customization is an effective business strategy, but many SMEs may hesitate to adopt it due to their limited resources. Furthermore, 4D printing technology needs to be further developed to enable the transition from the laboratory into industry. Accordingly, this study proposed a design concept that integrates 3D and 4D printing components as an alternative idea, and cited an example for independent designers and SMEs that leveraged the value of mass customization.

Fifth, a small experimental work was conducted to provide a real-life example of the concept discussed throughout this paper. Taking the example of the earring developed using this technology, other fashion accessory designs can also be created. For example, glasses' legs can be made by shape memory composites and attached to a 3D-printed glasses frame. Thereafter, the length of the glasses' legs made by shape memory composites can be adjusted when the material is exposed to different temperature stimuli. Additionally, by inserting shape memory composites into glasses' bridge, the distance between the two lenses can be also tailored.

Future research can conduct more experiments to accommodate different fashion accessory designs. Theoretically, any fashion accessory that has a fit concern, such as rings, necklaces, bracelets, watches, can all be customized using this design concept, so that the consumers by themselves can adjust the size of the accessory after the fashion item has been printed. The shape-changing property operated by consumers increases the product's uniqueness and hedonic value, thus reducing the possibility of return of a customized item.

From an industrial perspective, lastly, although 4D printing is still in the early stages, we believe it is time to establish practical business strategies according to the values 4D printing could add to the supply chains of the fashion industry. Hence, future research regarding 4D printing implementation and management is needed. Additionally, the integration of 3D-printed object and shape material is not only the expediency before the future improvement of 4D printing technology but also an innovative and feasible design idea that involves lesser investment in machinery, i.e., multi-material printer.

References

Bain, M. (2018, April 17). Nike has 3d-printed a stretchy, water-expelling, customizable sneaker. *Quartzy.* Retrieved from https://qz.com/quartzy/1254503/nike-just-debuted-flyprint-a-3d-printed-stretchy-customizable-sneaker-upper/

Berman, B. (2012). 3-D printing: The new industrial revolution. *Business Horizons, 55*(2), 155–162.

Bogue, R. (2013). 3D printing: The dawn of a new era in manufacturing? *Assembly automation, 33*(4), 307–311.

Carbon. (n.d.). The perfect fit: Carbon + Adidas collaborate to upend athletic footwear. Retrieved from https://www.carbon3d.com/case-studies/adidas/

Chavez, E. (2014, March 7). Pringle weaves 3D printing into its ready to wear fashion. *3D Printing Industry*. Retrieved from https://3dprintingindustry.com/news/pringle-weaves-3d-printing-ready-wear-fashion-24630/

Choi, J., Kwon, O., Jo, W., Lee, H., & Moon, M. (2015). 4D printing technology: A review. *3D Printing and Additive Manufacturing, 2*(4), 159–169.

Continuum. (n.d.). Projects. Retrieved from http://www.continuumfashion.com/projects.php

Cuzella, J. (2015). Fast fashion: A proposal for copyright protection of 3D-printed apparel. *Olorado Technology Law Journal*, *13*(2), 369–393.

Flower, I. (2017). Is mass customization the future of footwear? *Wall Street Journal*. Retrieved from https://www.wsj.com/articles/is-mass-customization-the-future-of-footwear-1508850000

Gall, K., Kreiner, P., Turner, D. & Hulse, M. (2004). Shape-memory polymers for microelectromechanical systems. *Journal of Microelectromechanical System*, *13*(3), 472–483.

Garcia, K. (2018, July 14). Fashion is popular for mass customization. *eMarketer.* Retrieved from https://retail.emarketer.com/article/fashion-popular-mass-customization/5b200c48ebd40003b84919ff

Ge, Q., Qi, H., & Dunn, M. L. (2013). Active materials by four-dimension printing. *Applied Physics Letter, 103*, 131901-1–131901-5.

Ge, Q., Sakhaei, A. H., Lee, H., Dunn, C. K., Fang, N. X., & Dunn, M. L. (2016). Multimaterial 4D printing with tailorable shape memory polymers. *Scientific Report, 6*, 311000-1–311000-12.

Gibson, I. (2017). The changing face of additive manufacturing. *Journal of Manufacturing Technology Management, 28*(1), 10–17.

Gonzalez, M. (2019, February 6). Revolutionary fashion designers who use 3D printing in their designs. *3Dprint.com.* Retrieved from https://3dprint.com/235318/revolutionary-fashion-designers-who-use-3d-printing-in-their-designs/

Hart, C. W. (1996). Made to order. *Marketing Management, 5*(2), 12–22.

He, Y., Guo, S., Liu, Z., & Liew, K. M. (2015). Pattern transformation of thermo-responsive shape memory polymer periodic cellular structures. *International Journal of Solids and* Structures, 71, 194–205.

Headrick, D. (2015). 4D printing transforms product design. *Research-Technology Management,* Retrieved from https://www.questia.com/library/journal/1G1-406163097/4d-printing-transforms-product-design

Hoskins, S. (2013). 3D Printing for Artists, Designers and Makers. London, UK: Bloomsbury Publishing Plc.

Hu, J. L., Meng, H., Li, G. Q., & Ibekwe, S. I. (2012). A review of stimuli-responsive polymers for smart textile applications. *Smart Materials and Structures, 21*(5), 053001.

Huang, S. H., Liu, P., Mokasdar, A., & Hou, L. (2013). Additive manufacturing and its societal impact: A literature review. *International Journal of Advanced Manufacturing Technology*, *67*(5-8), 1191–1203.

Huang, W. M., Zhao, Y., Wang, C. C., Ding, Z., Purnawali, H., Tang, C., & Zhan, J. L. (2012). Thermo/chemo-responsive shape memory effect in polymers: a sketch of working mechanisms, fundamentals and optimization. *Journal of Polymer Research, 19*, 9952–9987.

Invernizzi, M., Turri, S., Levi, M., & Suriano, R. (2018). 4D printed thermally activated self-healing and shape memory polycaprolactone-based polymers. *European Polymer Journal, 101*, 169–176.

Jacobs, B., &Singhal, V. (2017). The effect of the Rana Plaza disaster on shareholder wealth of retailers: Implications for sourcing strategies and supply chain governance. *Journal of Operations Management, 49*(51), 52–66.

Kowsari, K., Akbari, S., Wang, D., Fang, N., & Ge, Q. (2018). High-efficiency high-resolution multimaterial fabrication for digital light processing-based three-dimensional printing. *3D Printing and Additive Manufacturing*, *5*(3), 185–193.

Lampel, J., & Mintzberg, H. (1996). Customizing customization. *Sloan Management Review*, 38, (1), 21–30.

Leighton, M. (2017). A clothing startup founded by MIT grads is using 3D printing to make better, more sustainable clothes. *Business Insider.* Retrieved from https://www.businessinsider.com/ministry-of-supply-3d-printed-knits

Leng, J., Lu, H., Liu, Y., Huang, W., & Du, S. (2009). Shape-memory polymers: A class of novel smart materials. *Mrs Bulletin, 34*(11), 848–855.

Liu, Y., Du, H., Liu, L., & Leng, J. (2014). Shape memory polymers and their composite in aerospace applications: A review. *Smart Materials and Structures, 23*(2), 1–22.

Lowson, R. (2001). Customized operational strategies for retailers in fast-moving consumer industries. *International Review of Retail, Distribution and Consumer Research, 11*(2), 201–224.

Lu, S. (2016, January). Minimum wage in the apparel industry continues to rise in most Asian countries in 2016. Retrieved from https://shenglufashion.com/2016/01/

Lulzbot. (n.d.) What is 3D printing? Retrieved from https://www.lulzbot.com/content/what-3d-printing

Material ConnecXion. (2019, April). Material Library + Database. [7301-11 Polymers] Exhibited at High Point, North Carolina .

Mellor, S., Hao, L., & Zhang, D. (2014). Additive manufacturing: A framework for implementation. *International Journal of Production Economics, 149*, 194–201.

Melnikova, R., Ehrmann, A., & Finsterbusch, K. (2014). 3D printing of textile-based structures by fused deposition modeling (FDM) with different polymer materials. *IOP Conference Series: Materials Science and Engineering, 62*, 1–6.

Mendoza, H.R. (2018). 3D printed dress from Iris van Herpen pushes boundaries of fashion. *3Dprinting.com.* Retrieved from https://3dprint.com/201774/3d-printed-dress-iris-van-herpen/

Merle, A., Chandon, J. L., Roux, E., & Alizon, F. (2010). Perceived value of the mass-customized product and mass customization experience for individual consumers. *Production & Operations Management, 19*(5), 503–514.

Miaudet, P., Derré, A., Maugey, M., Zakri, C., Piccione, P. M., Inoubli, R., & Poulin, P. (2007). Shape and temperature memory of nanocomposites with broadened glass transition. *Science, 318*(5854), 1294–1296.

Michalik, J., Joyce, J., Barney, R., & McCune, G. (2015). 3D opportunity for product design: Additive manufacturing and the early stage. *Deloitte University Press*. Retrieved form https://www2.deloitte.com/content/dam/insights/us/articles/3d-printing-product-design-and-development/DUP_708_3DOpportunityProductDesign.pdf

Momeni, F., M.Mehdi Hassani.N, S., Liu, X., & Ni, J. (2017). A review of 4D printing. *Materials & Design, 122*, 42–79.

Mor, K. (2015). Kinematics: Origami inspired 4D printed clothing that might actually be comfortable to wear. *The New Stack.* Retrieved from https://thenewstack.io/kinematics-origami-inspired-4d-printed-clothing-might-actually-comfortable-wear/

Nike. (n.d.). Get help. Retrieved from https://www.nike.com/help

Oltuski, R. (2017). Why shop when you can print your clothes? *Racked.* Retrieved from https://www.racked.com/2017/4/24/15257660/3d-print-clothes-danit-peleg

Pei, E. (2014). 4D printing – revolution of fad? *Assembly Automation, 34*(2), 123–127.

Pei, E., & Loh, G. (2018). Technological considerations for 4D printing: An overview. *Progress in Additive Manufacturing, 3*(1-2), 95–107.

Probst, L., Monfardini, E., Frideres, L., Demetri, D., Kauffmann, A., & Luxembourg, S. (2013). Business innovation observatory: Advanced manufacturing & mass customization. *European Commision*. Retrieved from https://ec.europa.eu/docsroom/documents/13409/attachments/4/translations/en/renditions/native

Raviv, D., Zhao, W., McKnelly, C., Papadopoulou, A., Kadambi, A., Shi, B., Hirsch, S., Dikovsky, D., Zyracki, M., & Olguin, C. (2014). Active printed materials for complex self-evolving deformations. *Scientific Report, 4*(7422), 1–8.

Rayna, T., & Striukova, L. (2016). From rapid prototyping to home fabrication: How 3D printing is changing business model innovation. *Technological Forecasting and Social Change*, *102*, 214–224.

Razzaq, M. Y., Anhalt, M., Frormann, L., & Weidenfeller, B. (2007). Mechanical spectroscopy of magnetite filled polyurethane shape-memory polymers. *Materials Science and Engineering a-Structural Materials Properties Microstructure and Processing, 471*(1-2), 57–62.

Santo, L., Tedde, G. M., & Quadrini, F. (2015). Manufacturing of a shape memory polymer actuator. In *ASME 2015 International Manufacturing Science and Engineering Conference in Charlotte, North Carolina, USA*, June 8–12, 2015.

Schenk, M., & Seelmann-Eggebert, R. (2003). Challenge of mass customization manufacturing. In M, Tseng (Ed.), *The Customer Centric Enterprise,* Berlin, Germany: Springer.

Scott, C. (2018, December 24). Eco-friendly 3D printing at the center of designer's latest collection. *3Dprint.com*. Retrieved from https://3dprint.com/232528/eco-friendly-3d-printing-at-center-of-designers-latest-collection/

Senanayake, M. M., & Little, T. J. (2010). Mass customization: Points and extent of apparel customization. *Journal of Fashion Marketing and Management,* 14(2), 282–299.

Sun, L., Huang, W., Lu, H., Wang, C., &Zhang, J. (2014). Shape memory technology for active assembly/disassembly: Fundamentals, techniques and example applications. *Assembly Automation,* 34(1), 78 – 93.

Sun. L., Huang, W.M., Ding, X., Zhao, Y., Wang, C. C., Purnawali, H., & Tang, C. (2012). Stimulus responsive shape memory materials: a review. *Material & Design, 33*, 577–640.

TamiCare. (n.d.). Welcome to an entirely new generation of fabric. Retrieved from https://www.tamicare.com/

Tibbits, S. (2014). 4D printing: Multi-material shape change. *Architectural Design,* 84, 116–121.

Tibbits, S., McKnelly, C., Olguin, C., Dikovsky, D., & Hirsch, S. (2014). 4D printing and universal transformation. Retrieved from http://papers.cumincad.org/data/works /att/ acadia14_539.content.pdf

Vanderploeg, A., Lee, S.-E., & Mamp, M. (2017). The application of 3D printing technology in the fashion industry. *International Journal of Fashion Design, Technology and Education*, 10(2), 170–179.

Weller, C., Kleer, R., & Piller, F. T. (2015). Economic implications of 3Dprinting: Market structure models in light of additive manufacturing revisited. *International Journal of Production Economics, 164*, 43–56.

Xie, T. (2011). Recent advances in polymer shape memory. *Polymer, 52*(22), 4985–5000.

Yap, Y. L., & Yeong, W. Y. (2014). Additive manufacture of fashion and jewellery products: A mini review. *Virtual and Physical Prototyping, 9*(3), 195–201.

Zarek, M., Layani, M., Eliazar, S., Mansour, N., Cooperstein, I., Shukrun, E., Szlar, A., Cohn, D., & Magdassi, S. (2016). 4D printing shape memory polymers for dynamic jewellery and fashionwear. *Virtual and Physical Prototyping, 11*(4), 263–270.

Zipkin, P. (2001). The limits of mass customization. *Sloan Management Review, 42*, 81–87.