Fashion and Textiles

RESEARCH

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Exploration of 3D printing to create zero-waste sustainable fashion notions and jewelry

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Abstract

This research followed design as a research paradigm to apply zero-waste principles to 3D printing in efforts to ensure sustainable applications of 3D technology in the apparel and fashion industry. Researchers used Rhinoceros 5, Tinkercad, MakerBot Replicator 2 desktop 3D printer, and polylactic acid filament to create elaborate designs. This design research is the first successful attempt at 3D printing for biodegradable zero-waste fashion notions and accessories. The researcher employed design thinking and strategies to create objects without the use of rafts and supporters removing waste creation. Multiple attempts resulted in an acceptable outcome of five pendant designs for necklaces, two earring designs, and nine layer-designed buttons. The buttons were attached to a draped cape design utilizing 95% of the fabric. There is a considerable potential to use this disruptive technology in designing and creating fashions that are unique, sustainable (zero-waste), and made on demand.

Keywords: 3D printing, Zero-waste, Sustainability, Fashion, Technology

Introduction

This paper reports the results of an attempt to apply the zero-waste principle to three-dimensional (3D) additive printing to ensure sustainable applications of 3D technology in the apparel and fashion industry. 3D printing represents a relatively novel manufacturing technology that is associated with sustainability (Gebler et al. 2014) as it reduces waste. 3D printing (3DP) is the process of making a physical object from a 3D physical model. The process involves laying down many thin layers of material in succession based on a digital blueprint, usually a Computer Aided Design (CAD) file (3D printing, n.d.; Gebler et al. 2014). Zero-waste is a philosophy focused on "designing and managing products and processes to systematically avoid and eliminate the volume and toxicity of waste and materials, conserve and recover all resources, and not burn or bury them" (Zero-waste International Alliance 2009).

Mathematicians and engineers conceptualized 3D printing. The idea can be traced back to the 1880s, gaining momentum in the mid-1980s. Prototyping was its primary purpose during the 1980s and 1990s (Gebler et al. 2014; Rayna and Striukova 2015) with people exploring ways to take advantage of it over the last few decades (Hoskins 2013). The main identified markets for 3D printing include consumer products (e.g., apparel), medical components and transportation, and tool and mold manufacturing (Gebler et al. 2014).

Recent 3D developments have the potential to change the world, making 3D a disruptive technology. Its enhanced accessibility has provided a new platform for design, customization, and innovation. This disruptive technology also has an impact on everyday life. While still widely used for prototyping, different companies from a multitude of disciplines have been using 3D to print other materials. Common examples are live tissue for the medical industry, customized moulds for the dental industry, parts for both aerospace and automotive industries, print structures of different metals, and even entire buildings.

3D printing also has the potential to redefine the ready-to-wear fashion industry's supply chain (Tania 2017). Many fashion designers are taking advantage of this innovation, whether their focus is textiles, clothing, jewelry, notions or shoes. For instance, since 2008, Iris van Herpen has incorporated this technology into both her Haute Couture and women's ready-to-wear clothing designs. In 2011 she was the first designer to use 3DP technology to design a complete runway-ready dress (Logan 2015). Since then, she has designed innovatively using this technology (http://www.irisvanherpen.com/). Designers at Chanel used laser-sintering technology for parts of the iconic Chanel jacket (Hipolite 2015). The *Raviv's Manus vs. Machina: Fashion in the Age of Technology* grid pattern and 3D-printed collection garnered global attention (Farra 2017; Wyman 2016). Designers for Victoria's Secret, in collaboration with Shapeways, used a 3D scanner to create customized Swarovski-embellished angel wings for a model at a fashion show (Segall 2013). Zoe Dai used fused deposition modeling 3DP technology in her footwear designs (Krassenstein 2015).

Keeping in mind current developments and prospects in the fashion industry, the purpose of this design as research was to explore the potential of 3D printing for sustainable fashion. Respecting the rich potential for minimizing waste when using 3D technology (Gebler et al. 2014), the intent was to design customizable fashion notions and accessories made with environmentally-friendly materials using zero-waste sustainable design strategies. For clarification, there is a variety of 3D printing technology available including light polymerized, granular material binding and extrusion-based (Tania 2017). This design as research project used extrusion technology for additive manufacturing (AM), an innovative technology that has become increasingly available for artists, designers, and consumers (Reeves 2009).

Literature review

The literature review consists of six parts that support this 3D printing design research project. The six components include printing process, filaments, printers, software, apparel, product possibilities, designers' readiness for 3D technology in developing fashion innovations, and 3D printing sustainability issues, supporting the design as research reported herein, that being the principle of zero-waste in 3D printing in the fashion industry.

3D printing process

It is important to keep in mind that different 3D printers are capable of different things; however, the extrusion process is essentially the same, whether industrial or commercial. Extrusion printing, or Freeform Fabrication (FFF), is currently the most common and recognizable 3D printing process. The filament, which is wound on a spool, is passed through and heated in an extrusion head, with the temperature depending on the filament type. Next, the molten material is deposited onto the build platform. Layer upon layer is added as the platform slowly moves down, solidifying after extrusion and bonding as the process continues (Formlabs 2018).

If, upon accessing the CAD file (blueprint) for the object, the 3D printer deems an object unstable, it will put down a raft before printing begins. A raft is a horizontal latticework of filament that is located underneath the object. The raft helps with adherence to the build plate and reduces warping. If there are steep overhangs, supports are printed at the same time the object is printed. They provide added strength and prevent unwanted twisting or other deformations. The result is the solidified material or desired object (Formlabs 2018).

Although this process is slower when there are complex geometries, improvements are being made all the time. Using acetone in post-processing helps resolve adhesion problems. No other post-processing needs to be done other than sanding or coloration, if desired, with plastic-friendly paints (3D Printing Ally, n.d., http://3dprintingally.com/101.html). The reported project used extrusion printing but there are other types of 3D printing: stereo lithography, digital light processing (DLP), laser sintering or laser melting, inkjet, selective deposition lamination (SDL), and electron beam melting (EBM) (3D Printing Ally, n.d.).

3D printing filaments

3D printers heat and extrude plastic filaments (raw material). MakerBot uses virgin materials such as polylactic Acid (PLA) (corn-based), Acrylonitrile Butadiene Styrene (ABS), and flexible filament. PLA is preferred because it is biodegradable, has a lower melting point, and has higher dimensional stability as compared to ABS; however, PLA is water-soluble and not best for long-term wear (Pei et al. 2015; Samuels and Flowers 2015). Pei et al. (2015) reported significant findings through experimenting with warping, bond, print and flex with their choice of experimental filaments, PLA, ABS and Nylon 465, in both woven and knit fabrics made from natural or synthetic fabrics. They concluded that experimentation is needed to find solutions to challenges in using 3D printing for fabric applications.

In the meantime, Fair Trade plastic has both environmental and social components of sustainability. Joshua Pearce, a material scientist, created an ethical filament standard for 3D printing filament, following which the ethical filament was formed (http://ef.techfortrade.org). The ethical filament standard and mark is a work in progress. It will serve as a globally recognized fair-trade brand. Once ready, it will certify the ethical credentials of both sourcing and production of a filament. It will partner with waste-picking communities and local entrepreneurs to create a seamless process to create 3D printer filament from recycled waste materials. The proposed standard will grade filament using the Ethical Filament Value Chain. Proposed grading involves going through the following stages: plastic collection, cleaning, shredding and flaking, pigment and extrusion, quality checking, packing and dispatching. The proposed standard states that there will be two levels of requirement: minimum requirements to meet the ethical filament accreditation, however, suppliers may strive to exceed the requirements by reaching the higher level of standards (Ethical Filament 2015).

Other thermoplastic materials have also proven to be successful with 3D printing including nylon or polyamide. As for metals, derivatives of cobalt and aluminum are most commonly used along with stainless steel in its powdered form. Silver, gold, and titanium have recently been added to the metals list. Ceramic is another filament material but it must be fired and glazed to be finished rather than being finished immediately after printing as are the other materials mentioned. Standard A4 copy paper can also be used with SDL processes. Researchers have been and will continue to experiment with biological, or medical, materials to help the medical industry and patients. Finally, food substances (e.g., chocolate) have been experimented with over the last few years. Developments have also taken place to see if materials can work together (3D Printing Ally, n.d.).

3D printers and software

A variety of 3D printing and software design tools exist including Autodesk 123d Design, 3D Scanning, Tinkercad, Thingiverse, MakerBot Replicator 2 (an engineering-based modeling tool) (https://www.makerbot.com/), and Rhinoceros 5 (https://www.rhino3d.com/). They differ on learning curve, user-friendliness, applicability to specific end uses, features, design flexibility and creativity, power and versatility, price, and copyright issues (Fabian 2017). Some CAD software has an especially steep learning curve. Kwon et al. (2017) reported that even though the Rhinoceros 5 interface is user-friendly, it is very difficult to familiarize oneself with its tools and functions.

Different types of 3D printers that work with certain types of materials have been created to suit specific industries. Food printers have been recently introduced to print out flavored candy that can be enjoyed soon after printing is finished (Molitch-Hou 2015). Artists, such as ceramicists, have been using 3D technology to render their designs in the CAD software of their choice and print those designs with a ceramic-focused printer. The firing and glazing processes still have to take place; yet, artists gain a huge advantage in that their design can be easily replicated as files from CAD software can be saved for future use.

3D fashion product possibilities

The aforementioned 3D technological developments are providing opportunities for innovation and development especially in the fashion industry. 3D technology lends itself to customization that could actually eliminate fitting processes and simplify the overall design process (Shin et al. 2016). Customization applies to wearable technology as well as smart fabrics and textiles that are gradually being introduced to the market. Wearable technologies, such as the Fitbit or the Apple watch, track the number of steps taken in a day. Smart fabrics can allow cooling or heating when needed. They can also track body temperature, heart rate, and other bodily functions. The shoe and accessory-on-demand concept has also grown and allows consumers to have input, including having a say in the final product, particularly regarding the fabrication (Sun and Lu 2015).

Although many 3D printed garments seem impractical at this point, fashion and practicality are evolving. Examples of the former include the Iris van Herpen ice dress and the Dita von Teese dress made in collaboration with the Francis Bitoni Studio (http://studiobitonti.com/), the Michael Schmitt Studio, and Shapeways (http://www.irisvanherpen.com/). Although avant-garde, van Herpen has also contributed to this evolution in the fashion industry as have designers Noritaka Tatehana and Niccolo Casas.

Regarding practical applications, Robinson (2014) reported a collaborative project whereby 3D printed elements were incorporated into traditional wool fabric production to create innovative new looks and functions. In another experiment, Samuels and Flowers (2015) researched the possibility of 3D printing on cloth using MakerBot Replicator 2, chosen because it allows adjustments to the height and material of the base and temperature. They chose to test PLA appliqués on worn denim, which they taped to the glass printer plate of a 3D printer. From there, they first printed the .stl, or industry-standard stereo-lithography format files of small rectangular prisms on the fabric and later tested for tensile strength and washability.

Lynne MacLachlan, an engineer-turned-jewelry designer, has extensive knowledge in 3D technology, and she hopes that others in her field will take advantage of its potential and services (Smith 2014). As an example, 3D printed accessories can function as an art form that enables viewers to interpret cultural references through outward adornment. One such example is a neckpiece called *Beautiful Protector*. This piece demonstrates how 3D printing technology can provide an aesthetic experience when worn as an accessory and bridge the gap between advanced technology and traditional forms of adornment (Thurston and Mamp 2015).

Cubify, a commercial 3D printing company, recently introduced its new model *Fabricate*, made especially for apparel designers. Essentially able to make 3D textiles, the idea of 3D printed textiles and garments on the runways of *Fashion Week* is not so far out of grasp (Goehrke 2015). *The Atlantic* magazine recently published a brief technology news article about wearable technology and 3D printing (Meyer 2015). Customization will be possible using technology and the just-in-time strategy, with Meyer (2015) predicting that technology will allow read-to-wear companies to deliver same-day customized jeans and other products by 2025.

3D printing for shoes will have a significant impact on fashion. Innovation in performance footwear is being explored, as most 3D materials are extremely lightweight. Mass customization will allow consumers to create an accurate fit while also adding in their personal style (Black 2012). Geometrical freedom is virtually unlimited for AM, something not offered through any other singular process (Campbell et al. 2011). Weller et al. (2015) emphasized how customization is effortless with 3D printing and affirming that added detail comes at no additional cost unlike use of conventional technologies. Nike and the aerospace industry have supported and integrated this into their shoes and plane parts, respectively. Moreover, increased product complexity does not necessarily mean increased costs allowing further individualization from AM, which is different from other manufacturing processes (Reeves 2009).

Apparel designers' readiness for 3D

Although it is safe to assume that some artists and designers are familiar with this type of technology, not all are experts. 3D technology requires working in three dimensions, which means people have to be able to think in three dimensions; that is, they must engage in divergent thinking, approaching a problem from various angles (Hoskins 2013). As an example, sharing a design now involves sending a .stl file rather than an actual product (Campbell et al. 2011) truly making 3D printing the disruptive technology everyone is talking about now.

In actuality, apparel and fashion designers are by their nature divergent thinkers, making them well equipped to use 3D printing and technology since they already understand the human body and know how to change something from 2D to 3D. Examples include moving from flat pattern to a garment and using software to create endless possibilities of silhouettes and shapes never before attempted in garments. However, knowing how to convert flat patterns to a 3D garment does not necessarily help apparel designers adjust to using 3D modelling and printing technology (Sun and Lu 2015). Apparel designers face a steep learning curve when adopting 3DP technology (Kwon et al. 2017).

Although adoption of 3DP technology has its challenges, there are several advantages to fashion designers' utilizing this technology. The apparel and fashion designers' ability to 3D scan a body could lead to the elimination of prototyping, as the scan can put a person's exact measurements into a CAD program. From there, a garment, accessory, or brace can be created to the exact shape of the body, with no alterations, and be printed exactly to fit (Sun and Lu 2015). Another advantage of 3D technology is the way in which alterations can be done through software rather than altering a pattern by hand, which is still widely done today. The former can lead to further creativity in pattern making (Shin et al. 2016).

Actually, some apparel designers already rely on CAD software to create patterns that have specific, advanced measurements (Bodhani 2015). Recently, 3D Systems (2014) released their Bespoke™ braces for chronic condition scoliosis. The process is the same for each patient but the outcome is unique. After being fitted to perfection, the prototype is then made digital where it is altered and personalized even further. Finally, the brace is 3D printed with 3D Systems' selective laser sintering (SLS) technology. Chinese researchers from the National Rehabilitation Aids Research Center in Beijing, in partnership with German MD and Orthopedic surgeon Dr. Hans-Rudolph Weiss, have also utilized 3D printing to create customized scoliosis braces. Their goal was to make them more lightweight, sturdy, and less distinct (Krassenstein 2015) than existing options.

Sustainability of 3D printing

3D printing is synonymous with sustainability (Gebler et al. 2014). The use of 3D printing in manufacturing can assist in waste reduction. Because the entire object is complete once the printing is complete, nothing needs to be cut away. The object can be finished with sanding and painting if necessary. When applied to the apparel industry, using only 3D printing machinery rather than having a multitude of machines, could drastically cut costs and change the way in which the industry manufactures clothing (Sun and Lu 2015).

3D printing is based on additive technology, which uses only the materials that are required to create the object (Reeves 2009). Sometimes rafts or supports are required to enable the object to build correctly and lift up the printer platform; these create waste (Formlabs 2018). Although 3D printing is a sustainable means of manufacturing, ethical responsibility and environmental impacts must still be kept in mind (Gebler et al. 2014). The fumes and time needed to create a print can pollute but on a much smaller scale than subtractive manufacturing. 3D printing's waste is only 40% versus the waste produced by subtractive technologies and much of 3D printing waste is recyclable (Berman 2012).

3D printing has already proven to be an economical and cost-effective way for prototyping and manufacturing. The design and prototyping possibilities with 3D printing are limitless. As it uses CAD, a prototype can be quickly rendered and printed by the designer or the manufacturer (Weller et al. 2015) allowing them to decide, before mass production, whether or not the outcome meets their expectations. Additionally, designers and manufacturers may even print on-the-spot for consumers further eliminating waste. From a sustainability perspective, 3D printing also has the possibility of extending the life of a garment by assisting in making it multi-functional. For example, the *Microspace Transmorpho* dress may function as a full-length gown or as a mini dress, the silhouette and texture changing along with the length (Koo and Zarate 2015).

3D printing is a tool for designers that reduces waste by rapid prototyping. However, the application of a zero-waste philosophy (Zero-waste International Alliance 2009) to eliminate waste in the processes of creating innovative 3D printing designs has not been a consideration. That being said, 3D printing has the potential to add another perspective to sustainable fashion (Tania 2017).

Methods

Many researchers are exploring the potential of 3D printing but none have applied the philosophy of zero-waste to their designs. In this project, each design researcher took a different creative approach to designing and printing sustainable fashion notions. Researcher A has over 20 years and Researcher B has 3 years of design experience. The former created a cape and strove to design buttons (notions) using 3D printing technology. The latter created jewelry (pendants and earrings). These fashion items were designed with different sources of inspiration but with the same end goal of creating fashion items that are zero-waste and made from sustainable materials. The intent of this research was to develop a design process that minimized waste from 3D printing, ensuring a sustainable process and fashion outcome.

Design as research

Research is a systematic investigation of new ideas, solving problems and exploring outcomes that generate knowledge. Design is a purposeful arrangement of elements (Neuhart et al. 1989). As the fashion industry flourishes through change, fashion designers are constantly engaged in researching new designs, uses, materials, and perspectives (Seivewright 2012). Design as research is inquiry embedded in the design process (Chi 2001; Joost et al. 2016). It uses diverse strategies such as a study of materials, technologies, or developing products and services. Design as research "offers a medium of investigation for questions of broad concern [through practicing design] as a pursuit of knowledge, understanding" (Chi 2001, p. 250). In this paper, that concern is developing products utilizing zero-waste philosophy to ensure more sustainable fashion items.

Recent technological developments, including 3D printing, have opened a new space for creativity and innovation. Parsons and Campbell (2004) proposed that when designers engage with new technologies, the initial exploration is similar to the behavior of conventional, practice-based designers. "It is our argument that the creative process will evolve as designers become more skilled in the application of a new technology to the design process" (p. 89). The research-through-design method allows research through the process of design in which the knowledge generated is a result of cognition and creation thereby combining process and research, resulting in an object or artifact (Chi 2001; Faste and Faste 2012; Joost et al. 2016).

The artifact design is an outcome of the designer's internal abilities coupled with external toolkits (Faste and Faste 2012). In this study, the authors (researchers) followed these design process steps: (a) problem identification, which included identifying the design and technical aspects to explore; (b) conceptualization, involving the sketching and visualization of designs in 3D virtual space (using divergent thinking); and (c) prototype and solution whereby 3D printed designs were created and then finished (Parsons and Campbell 2004).

3D design tools

In their attempts to generate sustainable 3D fashion notions and accessories, both researchers trained themselves using a variety of relevant software training videos, identifying the design opportunities and limitations of each tool. Researcher A and B explored a variety of software design tools, settling on Tinkercad, Rhinoceros 5, and MakerBot Replicator 2. Initially, Autodesk 123d Design and 3D scanning were explored. Autodesk 123d design focuses on modelling simple shapes. 3D scanning was found to be not user-friendly, requiring multiple attempts to capture scan data. 3D was judged applicable to sculptures and similar objects. Thus, Autodesk 123d design and 3D scanning were excluded as design tools.

Tinkercad, a user-friendly software, was found to have limited design flexibility and creativity. Thingiverse is an open-source hardware design under creative commons where one can upload and customize designs created by others thereby limiting design innovation, exclusivity, and ownership. The researchers also explored available additive color to the material. They decided to use both Tinkercad, as it proved to be easy to use for basic shapes, and Rhinoceros 5 CAD tools for the extensive, detailed, and complicated design work.

3D design process

Researcher A created *Design 1 Ensemble* consisting of a cape and eight decorative, customized, layered buttons. Tinkercad was used to generate the alphabets and create holes in the buttons. Rhinoceros 5 was used to layer the word or shape in relief on the button. Researcher B created *Design 2 Ensemble* comprised of five statement necklace pendants and two pairs of earrings. Their designs emerged from exploring design as well as 3D modelling software in creating unique shapes and structures ensuring durability and zero-waste and using minimum plastic. Respecting the principle of sustainability, the researchers abstained from buying new colors of materials utilizing those already available at their institution.

MakerBot Replicator 2 is capable of printing from PLA, flexible filament, ABS and other materials. PLA filament was selected, as it is a biodegradable plant-based plastic. Both researchers used MakerBot Replicator 2 and available PLA plastic in white, clear, and blue colors (reducing waste). The settings of the MakerBot Desktop were explored for best design output. Settings include standard, low, or high quality profile to slice the 3D model. The quality profile defines the speed of operation, layer thickness, and surface texture. Layer height determines surface smoothness and is associated with quality and speed. Infill and number of shells determine the product's internal strength, weight, and durability.

Sustainability 3D design strategy

In their creative design as research method, the researchers hoped to develop a 3D process for building fashion notions and jewelry that yielded zero-waste. To that end, following a steep learning curve facilitated by Lynda.com tutorials, as well as several trial runs on the CAD-based tools, 3D modeling MakerBot software, and the 3D printer platform, the researchers developed expertise in design and design strategies. During the learning process, researchers were able to identify limitations and create desired shapes without waste.

Intricate designs in additive 3D printing typically require rafts and supporters. After printing, the raft and support have to be separated from the item in a tedious, unsustainable process, becoming waste (Formlabs 2018). Objects in this zero-waste project were designed thoughtfully, avoiding uneven or sharply angled surfaces to be printed that would need rafts and supporters. The width of the printed design details was sized to ensure that it was sturdy enough to hold the structure together and narrow enough to be lifted off the printing platform. Each item was designed with a durable flat base, as well as balanced, solid fills and meshes, with no overhanging parts, negating the need for supporters. These objects were then printed, lifted off the printing platform, and sanded to clean the edges as needed. Painter's tape sheets were used to facilitate easy removal of the printed object from the printer.

Results

Design 1 ensemble

Researcher A explored her personal sustainable fabric collection to find a medium for a 3D printing fashion accessory. The inspiration for the design 1 ensemble of button accessories and a cape came from a fabric remnant from a vertically integrated woolen mill. The jacquard fabric's surface design reflected regional pride (lakes, rivers). The fabric weight, limited remnant yardage, and the goal of zero-waste steered the garment design toward a contemporary-style cape with an oversized draped collar. The poncho-style cape was purposefully draped to display the Mississippi river (front view), key lakes at prominent locations (side arm drape), and to ensure maximum utilization of the fabric.

Researcher A was able to utilize 95% of the fabric. The cape was sewn and pieced together with flat seaming to manage bulk. The front was adorned with customized zero-waste 3D printed buttons to complement the fabric design. Two fabric-covered snaps were applied to create the closure. The raw edges were finished with a 3/8th" fringe for the hem and collar and a blanket stitch for the placket using yarns extracted from the fabric. These design decisions reflect the zero-waste philosophy (Zero-waste International Alliance 2009).

This fabric choice and cape design inspired letter-layered buttons with the name of the state and map in relief (see Figs. 1, 2, 3). The buttons complement the jacquard design of the local, biodegradable wool fabric that had a woven street and lake map of the state. To create the buttons, Researcher A started with the base letter shape and added holes using Tinkercad. Then, advanced Rhinoceros 5 was used to design the layering on the buttons. The buttons for letters A, E, I, M, N, and T have a word layered in the relief. The letter O has a map, shape, and the letter M layered in relief. The letter S has the letter M layered on it.

Each button took about 20 min to print. The 3D printing design work was a combination of simple letter shapes followed by the complex rendering of a map shape and layering. This process ensured that each button was printed without using rafts and supporters. The zero-waste buttons were designed to complement the sustainable fabric enabling experimentation and expanding the scope of design using available software and equipment. Researcher A developed intermediate skills in designing and printing in 3D. These designs can be further refined in terms of their sustainability

Fig. 1 3D Printed buttons attached on a cape (white PLA filament)

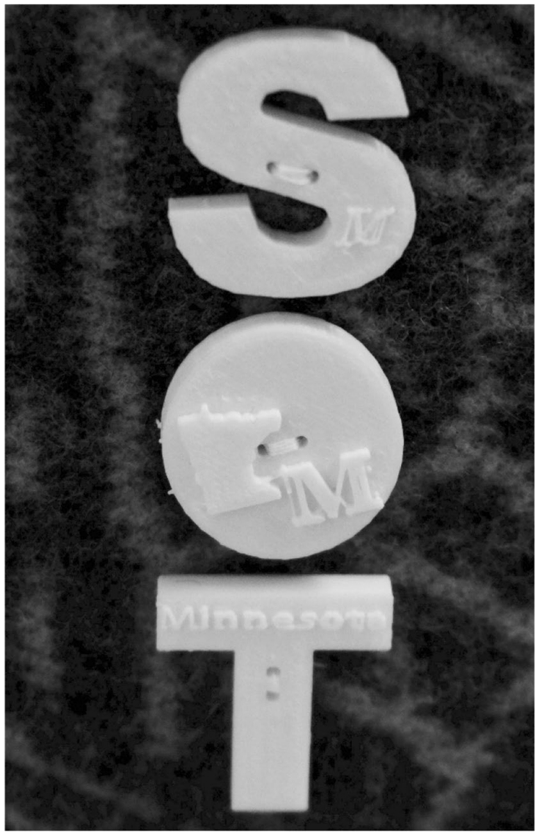

Fig. 2 Buttons with, state name or map or layered letter M

by exploring the layer height, printing speed and quality, infill, number of shells, and extruder temperature.

Design 2 ensemble

Design 2 ensemble entailed an assortment of statement jewelry items that derived their inspiration from a mood board that included 3D object figures and color inspirations. Researcher B reviewed several jewelry designs including those reported by Smith (2014) and Thurston and Mamp (2015). Selected figures from web-based media were pinned using *Pinterest* and later extracted and mounted on the mood board. Design Researcher B then sketched her unique design ideas, unique because of the design, specifications, and sustainability attributes (see Figs. 4a–c, 5a, b, 6a, b, 7, 8a, b).

The Rhinoceros 5 CAD software tool was used to create the pendant designs. As each pendant was of slightly different complexity than the others, each one took a different amount of time to print. Pendants numbered one through five (Figs. 4a–c, 5a, b, 6a, b, 7, 8a, b) took 1 h and 18 min, 1 h and 14 min, 1 h and 6 min, 56 min, and 40 respectively. In total, printing time was 5 h and 14 min (average 1 h per pendant). The time for printing varied based on the pendant thickness and extruder's movement for the design.

Researcher B also used gold paint finishing for two pendants to replicate metallic jewelry. The researcher explored sustainable paints but eventually used craft store plastic

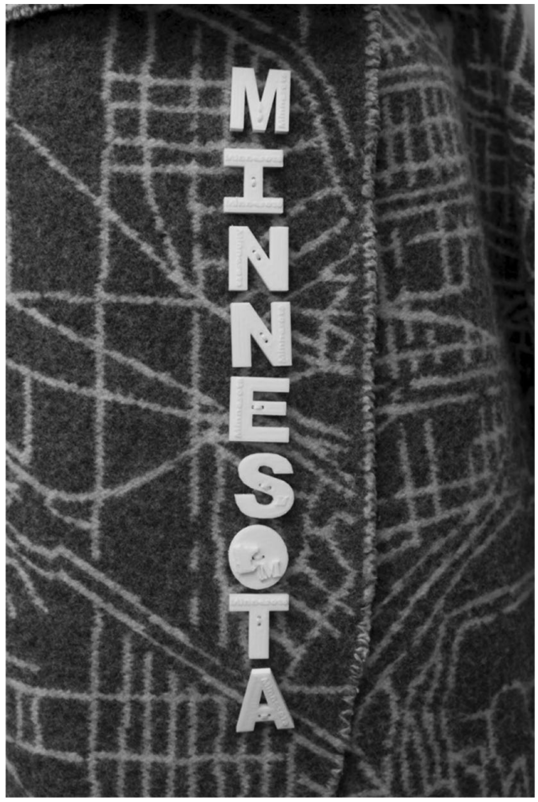

Fig. 3 Layered buttons

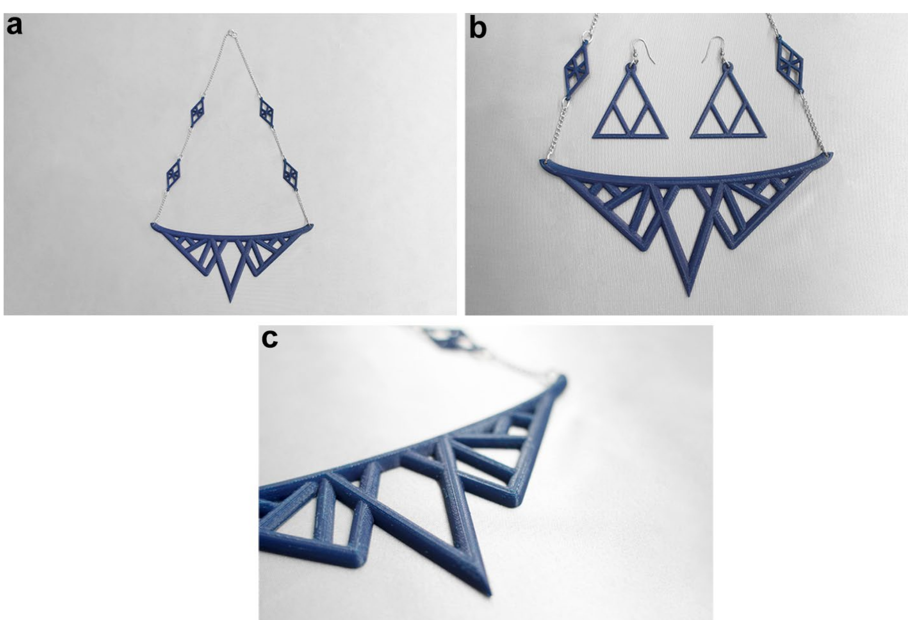

Fig. 4 **a** Jewelry pendant design 1(blue color PLA filament). **b** Jewelry pendant design 1 with earrings. **c** Zoomed view of jewelry pendant design 1

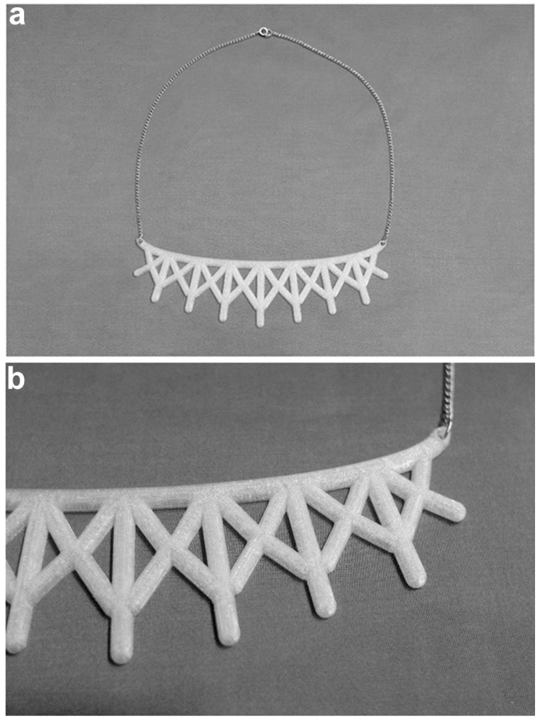

Fig. 5 **a** Jewelry pendant design 2 (clear PLA filament). **b** Zoomed view of jewelry pendant design 2

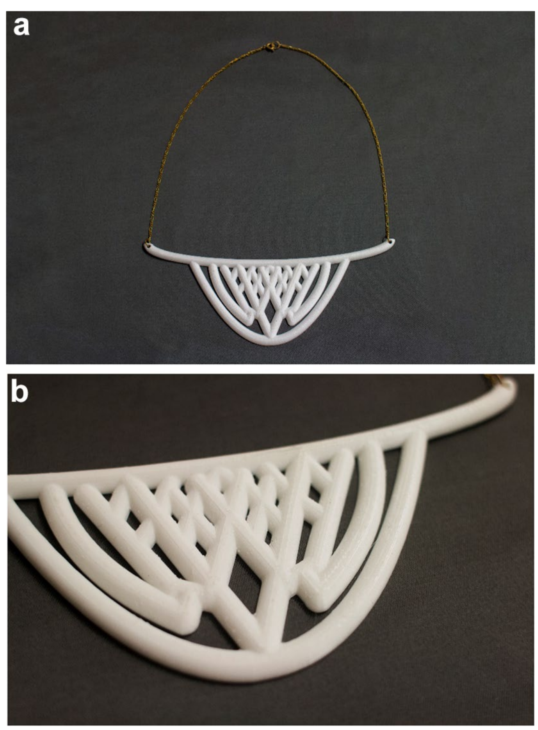

Fig. 6 **a** Jewelry pendant design 3 (white PLA filament). **b** Zoomed view of jewelry pendant design 3

Fig. 7 Jewelry pendant design 4 (white PLA filament brush painted with gold paint)

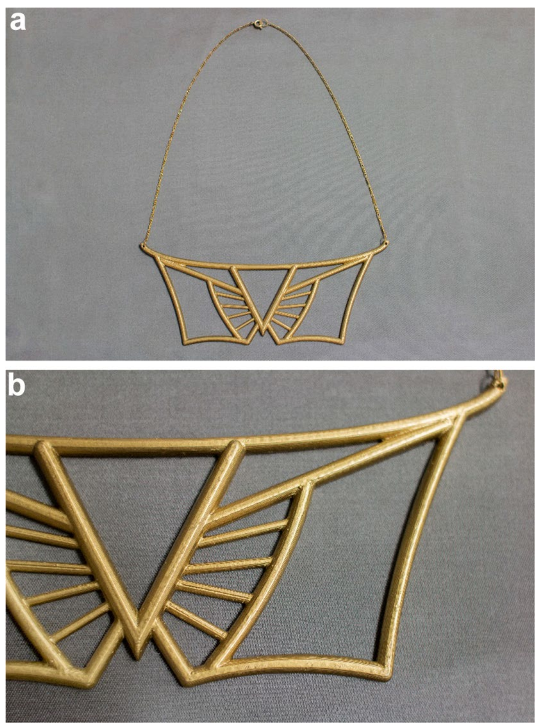

Fig. 8 **a** Jewelry pendant design 5 (white PLA filament spray painted with gold paint). **b** Zoomed view jewelry pendant design 5

friendly paints for aesthetics. Design 4 was painted using a brush, thereby preserving the surface texture of the pendant. Design 5 was painted using spray paint resulting in loss of surface texture. Each pendant was designed to include a variety of curves, points, thicknesses, and textures. These designs are only possible using Rhinoceros 5.

The smaller earrings took much less time to print than the pendants; averaging 15 min each (see Fig. 4b). If required, the final prints were hand sanded to remove rough edges. Researcher B developed intermediate skills in designing and printing in 3D. These designs can also be refined in terms of sustainability by exploring layer height, printing speed and quality, infill, number of shells, and extruder temperature.

Discussion

Design work as well as research and literature on 3D printing in fashion is in its infancy. Readiness to use this technology is on a continuum with many researchers exploring its potential and fewer designers actually successfully applying 3D printing to their work. Iris van Herpen, Shapeways, and Cubify are some of the leading designers and 3D companies but none of them have applied the philosophy of zero-waste to their design process as was reported herein. The authors were inspired by the zero-waste philosophy (Zero-waste International Alliance 2009), which gives fashion designers the opportunity to change the industry. The fashion items developed were created without generating any waste demonstrating a process that contributes to the body of knowledge on 3D printing with PLA plastic for the fashion industry.

3D printing additive technology provides unlimited geometrical freedom (Campbell et al. 2011). It is also considered sustainable as it directly prints the design (Gebler et al. 2014); however, by default, the printer chooses to include rafts and, in some cases, supporters to accurately print the design using the CAD file blueprint. These rafts and supporters are waste materials that have to be removed from the printed object after printing is completed. Fortunately, Berman (2012) reported that waste generation in additive printing is only 40% and recyclable. However, even 40% is too high for a zero-waste philosophy.

Consequently, the authors employed a design as research method and experimented with design strategies to be able to print without the use of rafts and supporters eliminating waste creation. They successfully designed and printed zero-waste notions and accessories made from biodegradable material using MakerBot Replicator 2 printer. This project is the first successful attempt at 3D printing for zero-waste fashion notions and accessories. The 3D printing technology industries are challenged to develop sustainable and durable materials as well as equipment that can print any design without waste. Such developments enhance the creativity and sustainability of 3D printing, especially if they respect the Ethical Filament Foundation's (2015) fair-trade filament standards.

However, as Pei et al. (2015) observed because the 3D filament material (PLA) used in our process is water soluble, future designers may need to use a different plastic as well as a different 3D printer to create zero-waste notions that can be applied to ready-to-wear washable garments. Designers may not be able to use biodegradable material. To address this possible sustainability and waste issue, additional research on washability and durability is needed to supply information on the suitability of the raw materials for end uses. Samuels and Flowers (2015) reported that PLA appliqués remained attached after a 45-min detergent-free, delicate wash cycle with warm water. They speculated, however, that "rougher washing cycles, higher wash temperatures, detergents, and dryer temperatures may cause PLA breakdown" (p. 20). In the future, when embracing the zero-waste philosophy, 3D printing technology industries will need to develop non-water soluble, sustainable extrusion filaments for use in apparel and fashion.

Both researchers experienced a steep learning curve when learning to use the 3D design tools (Fabian 2017; Kwon et al. 2017). The learning curve matters because it will require academia to train future professionals to be adept in existing and upcoming 3D technologies. Several variables that can be manipulated on the 3D printer's desktop and firmware also require training and practice to get optimum design results.

University-level training will be a challenge given the time commitment to learn the software. For example, a *3DP Digital Fashion Design Course* taught in a Korean university required 4 weeks of a 16-week course to train students on Rhinoceros 5 tools and functions (Kwon et al. 2017). Despite this learning curve, educating and socializing the next generation of fashion and design professionals to embrace the zero-waste philosophy, in concert with providing 3D technical training and developing practical skills, bodes well for sustainable 3D fashion design at academic, practitioner, and industry levels.

Limitations

This design as research was limited because of the shortcomings of the MakerBot Replicator 2 3D Desktop printer. The research was further limited by the size of build plate and type of filament used in addition to the challenges of learning the engineering-based CAD software Rhinoceros 5. Kwon et al. (2017) also reported difficulties in quickly learning Rhinoceros. Because the MakerBot prints with only PLA or ABS filaments, consideration of other durable (washable) and sustainable materials is necessary for future research. Future researchers could also explore other research variables including layer height, printing speed and quality, infill, number of shells, and extruder temperature, or other printers and materials. These may affect zero-waste achievements. Other sustainability issues related to 3D printing include emission of toxic gases and use of electric power and heat generation, issues that are beyond the scope of this paper. Such research could help this technology to storm the fashion world. Finally, although the authors were able to explore and design notions and jewelry, exploration of other available technologies and materials will facilitate further research in the area of producing sustainable, zero-waste 3D fashion items.

Conclusions

There is a huge potential to use this disruptive technology in designing and creating fashions that are unique, sustainable (zero-waste), and made-on-demand. The free availability and accessibility of many design software and 3D printers (Fabian 2017) allows designers to experiment and develop ideas that can transform the design industry in a big way. This technology is providing a landscape where humans and computers collaborate in design creation (Tania 2017). Indeed, the design as research approach used herein yielded zero-waste fashion accessories created through the interaction of the designers' thinking and 3D technology (Faste and Faste 2012).

Previous researchers (Black 2012; Meyer 2015; Shinet al. 2016; Sun and Lu 2015; Weller et al. 2015; White et al. 2015) have also found prototyping, customization, and on-demand design creation to be a very suitable application of 3D printing. However, none of them considered zero-waste or waste reduction in their design work. Be it rapid prototyping or on-demand creation, 3D printing goes hand-in-hand with sustainability (Gebler et al. 2014). The authors speculate that further strategies to develop critical viewpoint to expand the sustainability attribute and its application through divergent, 3D design thinking, including choice of philosophy, materials and equipment (Hoskins 2013), will shape new narratives of 3D printing and zero-waste, sustainable fashion.

Authors' contributions
AP and RG collaboratively learned the CAD and 3D printing software, conducted the review of the literature, and identified zero-waste design strategies. RG wrote the first draft of the manuscript; AP finalized the manuscript. Both authors read and approved the final manuscript.

Acknowledgements
Funding was provided by St. Catherine University, Minnesota (Grant No. NA).

Competing interests
The authors declare that they have no competing interests.

Publisher's Note
Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Received: 30 April 2017 Accepted: 5 July 2018
Published online: 27 December 2018

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