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Envisioning the era of 3D printing: a conceptual model for the fashion industry

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Abstract
The emergence of 3D printing technology in the fashion industries has led to a rapidly growing attention and discussion on its coming impacts, novel approaches and those relevant challenges involved in its supply chain integration. The purpose of this conceptual study is to examine the potential impacts and challenges of integrating Direct Digital Manufacturing methods, specifically 3D printing (3DP), in the fashion industry. To recognize and organize such integration, we first examine the nature of Direct digital manufacturing (DDM) in contrast to traditional manufacturing approaches. After that, a conceptual model applied to DDM integrated fashion industry was then proposed to address this change. With respect to 3DP, four areas of its direct and indirect impacts were prudently examined, which were primarily put on (1) design and product development, (2) sourcing and manufacturing, (3) retail, distribution and consumer, as well as (4) the sustainability optimization. The potential challenges of integrating 3DP, which ultimately leads to the DDM paradigm, in each of these areas were also evaluated. Beyond the identified impacts and challenges, this proposed conceptual model ultimately aims to help lay the groundwork, explore future research topics and curricula for the fashion field integrating DDM, focusing on the 3DP technology.

Keywords: 3D printing, Additive manufacturing, Direct digital manufacturing, Fashion, Textile and apparel, Industry

Introduction

A novel technology often leads to some forms of disruptions that are a result of the average consumer applying new tools in their everyday lives (Lipson and Kurman 2013). The birth of additive manufacturing, commonly known as three-dimensional printing (3DP) technology, took place in 1984 and is finally bringing us to a time of the third industrial revolution (Barnatt 2013). In the last few years, the capabilities of 3DP technology have generated much discussion and media exposure in industry and academia, detailing what may have been previously imaginable only in science fiction. To meet the trending technology of 3DP, the fashion industry has begun promoting innovation through exploring ways to integrate digital fabrication methods to promote innovation (Howarth 2013). In the last few years, 3DP has been explored in accessory and footwear markets (Nike football 2014; Treggiden 2014; Sher 2015). Other pioneers, like van Herpen (2017) and Chanel (Robinson 2015), in the couture fashion sector are experimenting with 3DP in expressing new aesthetics and material through conceptual art forms and believe that this technology holds much potential in providing a viable method to create fashion products in the future.

Currently, the core focus and feature of 3DP technology are embedded in its potential to interrupt the current supply chain and enhance the concept of product mass customization. The technology of 3DP is recognized for its potential to disrupt the traditional supply chain, in which offshore sourcing for manufacturing from developing countries will evolve into more domestic or local production (Winnan 2013). Consequently, this technology is also expected to provide alternative ways for sustainable manufacturing from the environmental, social, and economic perspectives in this evolving process (Lipson and Kurman 2013). At the same time, the rapidly growing and advancing 3DP market ultimately reflects the need for a new design approach in product customization and personalization (Delamore 2004) and integration of sustainable methods or systems in the 3DP era.

The purpose of this conceptual study was to examine the potential impacts and challenges when integrating 3DP technology into the fashion industry, where 3DP functions as a leading method in DDM. As to an extensive literature review was conducted and key themes were extracted to develop a conceptual model to illustrate the connections among various factors influencing the 3DP integration. To recognize and organize such integration, the nature of DDM was first examined in contrast to the traditional manufacturing approach or the current supply chain in fashion product manufacturing. After proposing the conceptual model of a 3DP integrated fashion industry, its potential direct and indirect impacts on four critical areas were explored, including design and product development, sourcing and manufacturing, retail distribution and consumers, and sustainability optimization. Finally, potential challenges were evaluated within these four areas as well as those challenges embedded in the transition towards DDM. Overall, this conceptual model aims to help lay the groundwork and explore future research topics and curricula for the fashion industry, particularly with a consideration of 3DP technology integration that will soon saturate throughout the current supply chain.

Direct digital manufacturing (DDM)

The discussion of 3DP technology must consider the overarching core concepts and trends in moving towards the future of manufacturing. Currently, 3DP is considered the leading technology in the emerging class of manufacturing, also known as DDM (Crump 2014; Holmstrom et al. 2016; Jadavji and Kesselman 2013), which has been referred to as additive manufacturing or free form fabrication. Expert has pointed out that “DDM is not a simple revision of existing manufacturing methods that makes the process faster; instead, it is a radical departure that fundamentally changes manufacturing” (Crump 2014; p. 2). DDM is essentially digital model based and automated production, and the 3DP technology involves fusing layers of one or more materials together using different types of processes, including Selective Laser Sintering (SLS), Fused Deposition Modeling (FDM), and polyjet processes. Commonly, 3D computer-aided design (CAD) programs are applied with 3D scanning technology to model and render the virtual representation of real products. Thus, it is notable in its ability to reduce cost in areas such as design and labor, particularly for customized products (Sisson and Thompson 2012).

Today, one of its foremost advantages is that it enables manufacturing complexity with reduced manual labor and increased variety in different product design options (Lipson and Kurman 2013) at a lower cost per part (Conner et al. 2014). Due to the 3DP capabilities in building the entire product in a single print job, DDM potentially requires much less or no assembly processes (Lipson and Kurman 2013). Consequently, DDM allows on-demand and on-site production assembly. It streamlines production schedules and only involves in accounting product level and assembly kits (Holmstrom et al. 2016) as opposed to the number of stock keeping units (SKUs) and bill of materials (BOM) in the traditional tool-based manufacturing. It reduces lot size and only involve counting the load of 3D printers (Holmstrom et al. 2016), which are much more compact and portable than most traditional manufacturing machines.

A conceptual model for integrating 3D printing in fashion industry

The integration of 3DP in fashion may eventually lead to a shifting paradigm in this industry. As we redefine this field for the future based on existing literature, such as industry domains previously proposed (Ha-Brookshire and Hawley 2013), there are four critical impacting components to consider in this conceptual model: (1) design and product development, (2) sourcing and manufacturing, (3) retail, distribution and consumer, and (4) sustainability optimization (Fig. 1). In the proposed conceptual model, the first three core sectors will vary in their potential impacts and the challenges to be faced, but those three components will actually operate in a circular and interrelated format, in which various segments or impacts may overlap and feedback into the prior or following sectors. The component covering sustainability optimization serves as a moderating factor that guides the level of impacts from integrating 3DP technology. Such impacts would lead to the new paradigm integrating DDM, which would complement or replace traditional manufacturing approaches.

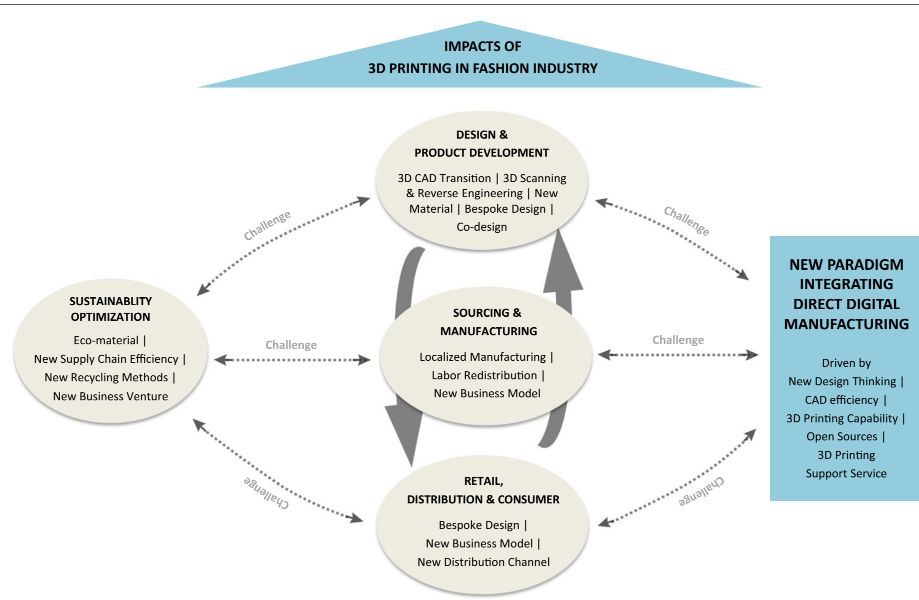

Fig. 1 The conceptual model of 3D printing impact in the fashion industry

Impacts on design and product development

Based on current notable literature, such as authored by Lipson and Kurman (2013), addressing the impact and future of 3DP and existing examples of 3DP integrated wearable products, including the Kinematics Dress (2014), works by van Herpen (2017) and Danit Peleg (2014), five major areas were identified to address the key impacts of 3DP integration on design and product development in the fashion industry. First, 3DP technology requires future talents to use a xyz coordinate system based 3D CAD modeling, rendering, and simulation programs, such as Rhinoceros and 3D Studio Max, in creating virtual product prototypes using real world measurements and references. Such programs are drastically different from what traditional fashion designers are accustomed to working with. Currently, 3D CAD/CAM integration available in fashion related programs such as Optitex only allow automated 3D avatar and garment simulation and are designed to build non-flat pattern based 3D objects. A designer would be expected to adapt to the logic of common 3D CAD programs and effectively visualize design, solve problems, and strategize ways of applying various 3D modeling tools (Vanderploeg et al. 2016). In addition, product design using complex structures would require the use of 3D computational design, which may involve tools such as the Grasshopper plug-in for Rhinoceros in visual programming.

Unlike the traditional design approach where designers rely on intuition and tacit knowledge to solve problems (Treadaway 2009), computational design enables encoding design decisions using computer language and predefines the steps needed to achieve a result (Kilkelly 2016). Fashion designers and product developers will be expected to adapt to the change in the order of operation in developing various garment structures. Further, 3DP pioneers today have also been advancing 3DP based wearable design through 3D CAD simulation technology. In response to the limitation in 3DP building volume, one can create hundreds or thousands of interlocking or articulating structures to allow movement using 3D simulation for material drape evaluation (Kinematics Dress 2014). This ultimately eliminates or reduces post-printing processes such as assembly. Moreover, fashion design and product development have traditionally relied heavily on hand-on based practices and intuitive decision making, and a steep learning curve exists in a digital design adaptation for designers who have more training in haptic skills (Danaher 2004; Harris 2005; Treadaway 2009). For 3DP based wearable product design, scholars (Sun and Parsons 2014) have found that traditional fashion designers would need to efficiently apply their spatial visualization ability (Kozhevnikov et al. 2010) and their tacit knowledge in order to effectively translate or convert the conventional hand-on based tools, procedures, and workflow into the 3D CAD processes.

Third, the 3D CAD modeling or rendering processes are often supported by the use of 3D scanning technology, which is capable of producing real world measurement data for a variety of objects from small jewelry pieces to large building structures. A human avatar is often utilized in the 3D CAD process as a "virtual dress form" for wearable product design (Sun and Parsons 2014). Such an approach would eliminate much of the procedures in traditional product development like various fitting sessions using live models. Alternatively, 3D scanning procedures may be utilized in a reverse engineering approach, in which various object iterations or modifications can be made quickly based on scan data without having to develop the base model from the start. The turn around time would consequently become reduced in the prototyping process, particularly considering the streamlined design modification timeline. Such versatility also stimulates various bespoke designs that accommodate targeted end users with a customized design feature or tailored fit (3D Printed XYZ 2013; Nike football 2014). Thus, the impact of integrating 3DP in the fashion industry would thus result in a change in design prototyping efficiency and the ability to move toward mass customization.

Fourth, the integration of 3DP technology would also require fashion designers to explore and understand entirely different types of materials, including both thermoplastics, such as polylactic acid (PLA), acrylonitrile butadiene styrene (ABS) and nylon, in form of filament, liquid, or powder, and metals, such as gold, silver, and brass. Each of these materials available is not only uncommon to the traditional textile material in its form but also has unique properties based on different 3DP processes applied. In addition, the properties of various 3DP materials can be manipulated through 3D modeling techniques that allows more flexibility and comfort in the final printed products. It is thus critical that fashion designers not only be able to design using 3D CAD modeling techniques but also apply the material knowledge in strategizing the overall design and product development process, especially considering the limitations in the existing 3DP processes, such as building volume. As a part of the material knowledge adoption, future designers will also need to explore various post-finishing processes and material maintenance methods, such as hand rinsing and air drying for thermoplastic materials.

Lastly, the nature of interdisciplinary knowledge and the skill sets expected for future designers would lead to new collaboration and team approaches. Currently, 3DP fashion pioneers such as van Herpen (2017) have been teaming up with experts outside of the field in creating unique wearable art that otherwise would have posed extremely high barriers for a traditional fashion design team. These collaborators are often engineers who are experienced in specialty materials and architects holds 3D CAD expertise. Today, many 3D printed fashion creations have also been a result of STEM (science, technology, engineering and math) field experts reaching beyond their fields and exploring the fashion and art realms (XYZ Workshop 2014). Overall, the boundaries of design and product development as well as those of designers and engineers, are becoming more blurred in the context of 3DP integration. One would need to be more well-rounded in obtaining the knowledge and skill sets relevant to various digital fabrication methods and be able to think holistically in conceptualizing and problem solving in product design.

Impacts on sourcing and manufacturing

A recent industry report suggests that 3DP technology may redefine new patterns for sourcing and manufacturing in the fashion industry (Global apparel manufacturing 2017). The three following potential impacts help explain the technology saturation and ability to complement the current supply chains. First, the most recognized major impact of 3DP integration is the shift to localizing manufacturing, which may become a feasible option for many fashion companies. Recent survey shows that more than 50% of manufacturing executives were at least considering shifting manufacturing back to the United States from overseas (Morris 2015). Retailers in the United States, such as Under Armour, believe the model of localizing manufacturing represents the future with the right amount of innovation and technology and know-how (Mirabella 2016). Through providing low-volume and tailor-made products on-site, technology like 3DP would also help reduce material-supply risks, supply chain network complexity and inventory costs (Laplume et al. 2016). Furthermore, one does not have to be concern with finding large warehouses to store traditional machinery and products, hence reduced fixed capital costs (Sisson and Thompson 2012; Lipson and Kurman 2013).

Second, the apparel manufacturing offshoring approach is essentially factor-cost differentials, particularly for labor arbitrage. Some of the largest exporters for the fashion industry would no longer serve as the cheapest producer in the future. Experts have noted that 3DP technology has the potential to reshape the global fashion supply chain by altering its geographic span and density (Laplume et al. 2016). Since the labor input in 3DP is relatively modest compared to traditional manufacturing, the comparative advantage of Asian countries on wage differentials is diminishing (Jing 2015). Statistics suggest that in developing countries like China, where monthly wages of the 23 million textile workers averages at ¥4000 (RMB), or $650 (US) a month, manufacturers who rely on exports would face financial pressure (Jing 2015) in the localized manufacturing approach. Consequently, the competitive advantage in global specialization would lose significance.

Third, lead time is a critical factor in the fashion industry that affects sourcing strategy. To meet consumer's changing needs, fashion products are expected to be manufactured and delivered in a much more efficient manner to avoid overproduction and loss of competitive advantage. In this case, lead time becomes even more important than the overall cost. Currently, when raw materials and components that are sourced in India and South Korea, and production is planned to occur in China, one must wait until the arrival of all materials before proceeding to the actual production and assembly phase. In contrast, 3DP may shorten lead times through immediately making products available via on-site manufacturing. Also, 3DP has the capability of eliminating or reducing product assembly processes. Therefore, the amount of intermediate goods would be expected to decrease (Laplume et al. 2016). Coupled with shorter lead times, greater control over inventory, rising demand for high-quality apparel and rising consumer income would further incentivize manufacturers to relocate to the United States.

Impacts on retail, distribution, and consumer

Many scholars and experts have noted how 3DP could be a huge part of the retail industry's future (Nordmark 2015; Luke 2014). One major phenomenon in the rise of 3DP technology application is the exponential increase in the demand for commercial based 3D printers. Data from 2013 to 2014 alone reveals the 3D printer market has seen a 200% growth in the United States (Tracking the growth 2014) and projected the global 3D printer market is projected to reach $9.6 billion (US) by 2020 (Deacon 2014). In North America, this market is expected to account for 49% of global revenue in 2018 (Deacon 2014). Leading 3D program company Autodesk also foresees half of all households in even developed countries will own commercial 3D printer within a decade (Nordmark 2015). Designer, Danit Peleg was able to produce the first apparel collection using commercial desktop FDM printers (Danit Peleg 2014, 2015). Consequently, this phenomenon reflects the increasing demand in product personalization and customization. Modern consumers truly care more about exclusivity and desirability.

Unlike traditional manufacturing techniques in which many different molds are needed to produce product variety, 3DP is capable of creating such variety without the additional manufacturing costs (Nyman and Sarlin 2014). This also reflects the increasingly influential maker's movement, in which technology enthusiasts enjoy the hands-on, do-it-yourself (DIY) process in creating one-of-a-kind customization for themselves (Lipson and Kurman 2013). This unique trend has led to the rapid growth of bespoke design in various product markets, such as the niche for 3D printed custom jewelry (e.g., Shapeways). Today, certain consumer generations, such as the millennials, are taking on more influential power in the fashion industry, which has the inclination toward changing the traditional picture in business, economics, and lifestyle. Therefore, fashion retailers need to consider how to employ radically different approaches in retailing (Millsaps 2015). The second key impact in this sector falls in the alternative business models that have quickly surfaced in meeting the increasingly diversified consumer demand. Currently, there are three main approaches for consumers to obtain 3DP products and/or experience product customization.

Consumers can buy finished fashion products directly through retailers or designers that currently market 3DP based or integrated products (e.g., Under Armour Architech footwear). They can also participate in the design process via online, website or mobile APP based, or offline 3DP stores (e.g., Feetz). Alternatively, consumers can make 3DP products using commercial 3D printers directly at home, which is particularly convenient for small product such as fashion accessories. More prominently, online print shops have been taking advantage of this trend in recent years. They are conveniently located for consumers and offers tolerable delivery charges. Shapeways.com hosts a vibrant marketplace for art, jewelry, toys, and mechanical parts among other things that are all manufactured on demand and is a common solution for hobbyists and professionals alike to create customized objects with a reasonable lead time (Shapeways 2017). It essentially adopts the Etsy business concept but features the 3DP capabilities for product customization. Hobbyists are thus allowed the opportunity to market and feature unique products and ideas with a limited startup investment. In the future, more apparel products, such as the N12 bikini by Continuum Fashion, may be sold via such online platforms (N12, n.d.).

Third, to attract the attention of today's fashion consumers, retailers should also be watching an entire industry pivot and restructure distribution channels under the influence of the 3DP technology. Online, local print stores as well as household consumers will complement to traditional manufacturing/distribution and create the 3D Printing value chain (Laplume et al. 2016). New dynamic flexibility in localized distribution would be needed for future 3D integrated Omni-channel retailing. By producing on-site or near the point of consumption, shipping costs for 3DP based fashion products would be drastically reduced (Lipson and Kurman 2013). Online design repositories and various distribution channels would reshape consumer behavior. At the same time, transportation costs for 3DP based fashion products would reduce drastically, as they would be produced on-site or near the point of consumption (Lipson and Kurman 2013).

Furthermore, in meeting consumers' needs, the characteristics of quick responsiveness and customization in 3DP technology are expected to be most suitable for the fashion industry. Fast fashion consumers desire products that capture the latest trends, which challenges the fast-fashion system to combine quick response production with enhanced product design capabilities (Cachon and Swinney 2011). Companies such as Zara have a swift or even weekly turnover of their shop collections and thus have a higher demand for short lead time (Hansen 2012). The 3DP technology is thus likely to provide a better solution for meeting the costumer's growing demands for fashion trends.

Impacts on sustainability optimization

The technology of 3DP has great potential in sustainability optimization from the environmental, economic, and social perspectives. First, the core sustainable advantage and the nature of this production method are embedded in its approach to minimal wastes and the reduced by-products. The two types of 3D printers, selective binding and deposition processes, essentially build objects based on a blueprint from the CAD file, only applying materials where the object requires. Considering the vast potential in the CAD based design process and the related benefits of 3DP integration in the current supply chain, experts expect reduced carbon footprints and an immense percentage of potential inputs such as energy saved (Lipton and Kurman 2013). In 3DP technology, some selective binding printers such as the Selective Laser Sintering (SLS) process use powder-based material that can serve as both building and support material in printing. It allows more than 50% of the material to be recycled with virgin powder for future print jobs. The US Department of Energy has estimated that the 3DP manufacturing method can reduce energy consumption by 50% compared to the traditional subtractive manufacturing approach (We can't wait 2012). A forecast generated, using an environmental and economic impact model, suggests there can be a global reduction in cost of $170 to $593 billion (US) and 5% in energy and CO_2 emissions of industrial manufacturing by 2025 (Gebler et al. 2014).

To advance further in sustainable innovation, a form of Solar Sintering based 3D printer is capable of using solar power to not only run the printer but also to ingeniously uses concentrated sunlight as the printer's "laser" or heat source to fuse the building material, sand, to form the object (Lipton and Kurman 2013). As the sand melts, the object can be transformed into a strong glass material without added adhesive, and would be able to be ground back into sand (Lipton and Kurman 2013). Such an approach has the potential to achieve the cradle-to-cradle model (Braungar and McDonough 2002), in which products are designed and made in a regenerative way.

Second, from a recycling standpoint, 3DP technology is capable of making a large impact on the way we use and reuse everyday materials and products. Currently, 3DP technology is capable of recycling polyethylene-based material, such as the content found in milk jugs, into 3D printer ready filament (Lipton and Kurman 2013). Typically, only 10% of all plastics we use are recycled due to the high cost of machining plastic and the potential for contaminations in the process (Hakkens, n.d.). Furthermore, plastics such as PLA and ABS can be recycled into filaments for the 3DP process like FDM (fused deposition modeling) using low temperatures. Various start-up companies are also actively sourcing and developing "valuable" plastics using methods of extrusion, rotation, oven heating, and injection (Hakkens, n.d.). Experts believe that soon people will be able to recycle their own household plastic into material suitable for a desktop personal 3D printer (Lipton and Kurman 2013) using centralized and home-based recycling systems (Kreiger et al. 2014). The potential impact of such a process would conserve 100 million MJ of energy per annum and significantly reduce greenhouse gas emission (Kreiger et al. 2014). Technology is even now available for recycling 3D printed products on a commercial scale using the 3D-Reprint concept (Krassenstein 2014). At the convenience of home, consumers are thus able to purchase desktop recycling machine to generate 3DP material, commonly in plastic filament form, from existing 3D printed based or plastic based product to use in future new print jobs (e.g., Precious Plastic, 3D Brooklyn).

Consequently, the nature of various 3DP processes may inevitably lead to the development of a new recycling system for both fashion and non-fashion products. At the same time, related 3DP and recycling support business opportunities would take a role in the scheme of recycling. Today, companies like the ProtoPrint enterprise of India are already following a new business model through focusing on social sustainability efforts. Its main mission is to offer job opportunities to the impoverished members of society through recruiting local waste pickers who will be able to earn 15% more than their typical income (Molitch-hou 2014).

The new paradigm of integrating direct digital manufacturing

The above impacts mentioned would ultimately lead to the development of a new paradigm integrating DDM, which would be lead through a few critical motivating drivers. Aside from the above mentioned four areas of impact, design and product development, sourcing and manufacturing, retail, distribution and consumer, and sustainability optimization in a 3DP integrated fashion industry, there are also challenges between the major components in ultimately achieving an efficient fashion supply chain.

The challenges in design and product development

One of the biggest obstacles in integrating DDM in the current supply chain, particularly using technology like 3DP, is embedded in the design and product development sector. Designers today will be mostly challenged in developing digital design skills, such as applying 3D modeling CAD programs, and translating traditional training knowledge into the virtual design environments to develop various unique yet efficient and sustainable design and product development processes. The current 3D CAD modeling and rendering programs are based on x–y–z coordinate system, including Solidworks, 3D Studio Max, Google Sketchup, and Rhino were not developed with the traditional fashion designer in mind. They are limited in a type of structure and its intuitive interface for typical wearable product design. Often, the software terminology or jargon used is rather foreign to fashion designers who are familiar with techniques from the traditional studio.

Traditional prototyping and production processes for fashion designer, such as 2D flat patternmaking and 3D draping, often involve using muslin to develop a sample garment to fit the preselected mannequin. These processes require the designer to understand real material properties and dimensions of the body form and develop their abilities in dimensional crossing from 2D to 3D, or their spatial visualization ability, in various problem-solving stages (Gitimu et al. 2005; Orzada and Kallal 2001; Workman and Ahn 2011). However, traditional training for fashion designers commonly does not include the 3D modeling and rendering techniques using digital fabrication methods, such as 3DP. Previous studies focusing on design cognition in 3D modeling of wearable products has suggested that a designer usually faces a challenge in accurately perceiving haptic and visuo-spatial experience in the virtual prototyping process (Sun and Parsons 2014). Even considering designer's experience in 2D CAD programs, scholar has found the digital crafting process may result in an exhausting experience, and individuals with more training in haptic skills are more likely to deal well with the challenges in the virtual design environments (Treadaway 2009). Consequently, the designer's foremost challenges in this transition may be largely embedded in transferring traditional knowledge into the 3D CAD environment and converting traditional techniques and approaches terminologies into available digital 3D CAD tools.

Furthermore, considering the challenge of developing a sustainable design and product development process, today's designer in today also faces the challenges in learning new material, particularly 3DP material and relevant 3D printer capabilities. The current advancement in 3DP material is common in thermoplastics, such as nylon and polylactic acid (PLA), but has also expanded to metals, such as stainless steel and silver, glass, and even paper materials. Although these materials may not be entirely foreign to the fashion industry, the way in which these materials are applied, including melting filament, sintering powder, and heating liquid, changes their properties and capabilities for various product developments. Moreover, in order to design sustainable products, a designer in the future will be probably be challenged to take consideration of a product life cycle analysis and a material's recycling capability for recycling.

Considering the transition from the traditional design and product development process to a DDM integrated approach, the challenge is also embedded in mainly training and educating talents with new knowledge and skill sets. First, the tacit knowledge from traditional training will need to be converted to information applicable in the virtual design world, hence the 3D CAD process where new digital tools will apply. The skill of translating 2D ideas to 3D models or prototypes will become more critical in developing the spatial visualization skill needed for such CAD processes. Second, the boundary of knowledge needed for design and product development processes will become blurred, as a designer will be often required to not only adapt to 3D CAD processes but also learn new materials, relevant 3DP technology and applications. Third, individuals who work in the design and product development sector will be required to speak the language or understand terminology and foundational concepts from both traditional designer's and maker's worlds. Often, design processes in a DDM integrated supply chain require lots of interdisciplinary efforts, and a designer in the future would be challenged to work with those talents who are unconventional partners to the traditional process. Finally, technology such as 3DP offers the potential for a much quicker turn-around time and energy efficient production. Designers would need to evaluate new sustainable practices in design methods, approach and/or work flow. Industry will thus face another challenge in proposing option in talent training approach as well as talent outsourcing strategy in the early transition periods.

The challenges in sourcing and manufacturing

The integration of 3DP technology integration would ultimately change the current industry from the traditional labor-intensive to knowledge-intensive and capital-intensive manufacturing. Although challenges are apparent in the sourcing and manufacturing sector, one may identify new sources of competitive advantages. First, oversea industry suppliers may be concerned over ways to achieve a new competitive edge and sustain their power in the global supply chain. This may also result in a conversation regarding corporate social responsibility, such as environmental efforts and ethical labor practices. One of the critical and foremost questions is what will happen to millions of unskilled or low-skilled workers currently employed in the fashion industry. Manufacturing intensive countries that currently hold the advantage in cheap labor would be required to consider labor redistribution (Laplume et al. 2016). On the other hand, when manufacturing shifts locally, the question becomes how would developed countries like the United States support the DDM integrated fashion industry.

Second, other major challenges in manufacturing include a relatively slow printing speed, a limited product size in printer, product parts assembly management, materials availability and their property limitation. In some 3DP processes, quality may also pose a challenge. Particularly, the cost in common 3DP materials is currently much higher than those from traditional manufacturing, but it holds some competitive advantages due to much higher material efficiencies (Reeves 2008). Therefore, it is necessary for fashion retailers to make sourcing decisions beyond simply chasing low-cost labor and, instead, evaluating total factor performance across material efficiencies, transportation cost, storage cost, capital, and trade policy. Third, policymaking, such as for 3DP based products, becomes critical as new approaches are needed to support DDM integration (Sisson and Thompson 2012). For instance, current tariff systems and country of origin standards would be revisited for 3D printed products that are embedded with patented design using customized materials. Consequently, the follow up concerns would also include how international trade policy will evolve in 3DP integration. Due to the potentially for intermediary goods to be eliminated, goods-related agreements would be replaced by services-related agreements (Trade regulation 2016). In addition, as new formats of trade approach and new raw materials emerge, many World Trade Organization (WTO) rules will not apply in the absence of cross-border trade (Trade regulation 2016).

Overall, manufacturing companies would have to face some huge challenges in seeking a way to adapt, organize, and operate in a fundamentally different approach to produce 3D printed products from a DDM integrated supply chain to meet demands from a diverse customer base. It would further require a capital investment for industrial or commercial 3D printers, technology innovations, inventory/logistics adjustments, and managerial talents. New strategies or systems will be needed in managing long-term risks and near future transitions and uncertainties. In consideration of supporting industry talents in a 3DP integrated supply chain, fashion education would be expected to reconsider existing curricula to include new knowledge and skills in domestic sourcing, 3DP integrated supply chain management, smart or DDM manufacturing, as well as collaborative approaches with the design and product development sector.

The challenges in retail, distribution and consumer

A 3DP integrated supply chain will also result in a huge impact on the way products are distributed, promoted in a retail environment, and interacted with consumers through personalization services. First, one major outcomes is that it will essentially lead to a shift and advantage in the "local for local" production model that involves customization for a specific end-use or individual consumer (Mirabella 2016). Fashion retailers such as Under Armour have spear headed in this approach with its newly implemented manufacturing center, the Lighthouse (Mirabella 2016). However, localized manufacturing cannot survive without the adequate support services. Given the need for shorter turnaround time to support local production, barriers exist in building a quick-turn distribution network and seeking efficient contract factories that can support both conventional and smart industry needs. On the other hand, experts do point out that "even if 3DP is a complement to, rather than a replacement for, mass production, it will serve in generating new economic activity" (Winnan 2013, p. 225).

Second, considering various new business models that support 3DP based product customization, consumers in such a supply chain may carry a bigger role in product design and production. However, they do not currently have reliable information about how, what, and where one can learn, create, customize, and purchase 3DP fashion products. Third, the issue of intellectual property protection and ethics will become another concern when product design involves members from both business and consumer parties. With a digital file and a 3D printer, anyone could print products that are copyright protected. Fourth, consumers' perceptions toward 3D printed products is very limited in both industry and academia. Current platforms capable of 3DP products, such as mobile applications and online websites, have been attractive to individuals who are part of the maker movement (O'Toole 2014). However, retailers are limited with effective approaches in understanding consumer needs. In addition, new businesses may also consider the ways that social media and online platforms that can contribute to consumer education in 3DP based or integrated products as consumers are beginning to experience, question, and seek guidance.

In the face of this ferment of change, fashion businesses need to arm themselves with deep knowledge in the consumer profiles in the 3DP product market and the influencing factors in consumer's purchase intentions towards 3DP based or integrated products. In addition, the fashion retailers must embrace the technology while investing in interdisciplinary exploratory with aspects of new IT knowledge, business knowledge, and product knowledge. Correspondingly, the current fashion education that concentrates on merchandising and retail planning and buying would need to consider providing students an interdisciplinary exposure in localized manufacturing and distribution, prosumer based entrepreneurship, as well as advanced digital retail and marketing technologies.

Drivers in the DDM integration

The integration of DDM in the future would be stimulated and influenced through several drivers. First, the "changing supply chains induce the need for more information technology-related skills in labor", and "this includes both a paradigm shift in design-thinking as well as the need to increase training and education in digital manufacturing" (Gebler et al. 2014, p. 166). As the industry integrates new manufacturing technologies such as 3DP, all stakeholders will need to adjust to the new digital fabrication workflow, problem-solving approaches and developing strategic plans to accommodate the rapidly evolving demands and needs. Such responses include, not only the design, entrepreneurial opportunities, and sustainable practice aspects, but also a global shift in policy establishment and intellectual property guidelines. One other influential factor in new design-thinking is the creative approaches in bridging traditional design and non-design disciplines. Therefore, education programs also face an urgent need to adjusting to new knowledge and interdisciplinary collaboration demands (Gebler et al. 2014).

Second, traditional designers need to develop the skills in applying efficient 3D CAD processes for transforming abstract design ideas into real prototypes or outcomes. Currently, most do not have foundational training in 3D CAD programs and often end up working with 3D modeling experts from other disciplines or professional 3DP companies. Thus, it is urgent that fashion designers acquire knowledge in new material and technology and gain skill sets in developing 3D CAD based objects independently. It is also important for fashion designers with traditional hand crafting backgrounds to recognize the differences between the two modes of crafting and allow time to develop tacit knowledge and time to adapt to the digital process (Philpott 2010).

Third, the speed in which DDM can be integrated efficiently also relies on the capability of relevant technologies. The current advancement in 3DP has expanded the material availability and the relevant ability in material mixing during production. However, limitations still exist in material resilience and feasibility for wearable product development. At the manufacturing scale, product quality for real world proofing and product post finishing techniques and processes is yet to be tested. The capability in 3DP technology will also impact the strategy implemented in areas including production planning, labor distribution, and new talent training. Fourth, various DDM technologies are currently coupled with the new trend in open sources, such as online 3D models for 3DP, free software for 3D model processing, white paper for do-it-yourself tutorials ranging from learning new 3DP materials to building a 3D printer (e.g., RepRap). These repositories would thus support individuals from various supply chain sectors, especially the prosumer group. Previously, study has examined the investment on household 3D printers that utilize open source downloads and found they would yield a return over 100% of return in 5 years (Petersen and Pearce 2017). Consequently, the movement of home manufacturing, localized manufacturing, and the demand in product customization would become more viable in the near future (Laplume et al. 2016).

Lastly, DDM saturation cannot stand alone without relevant 3DP support services. Companies like UPS has expanded 3DP services nationwide to meet growing consumer demands. Currently, the enterprise software company SAP has partnered with The UPS Store, and other major 3D printer brands to create a dynamic global network for distributed manufacturing (Dever et al. 2017). Such support services will greatly increase cost-effectiveness for small business, reduce product parts inventory, enhance same day delivery, and allow opportunity to access to customer groups who have yet to invested in 3DP.

Conclusion and limitations

The coming era of 3DP will lead to a fundamental and revolutionary change in the global fashion supply chain. The new paradigm will inevitably lead to the ultimate adoption of DDM that is stimulated through new design thinking, efficient 3D CAD processes, adequate 3DP capability, available open source, and flexible and dynamic 3DP support services. In order to adapt and transition in a timely and effective manner, it is urgent for the fashion industry to seek a novel strategy and the relevant initiatives to support training and education for manufacturers, retailers, entrepreneurs, designers, and consumers. The challenges for the core areas of the proposed conceptual model [(1) design and product development, (2) sourcing and manufacturing, (3) retail, distribution and consumer] will need to be closely evaluated with the opportunity in leveraging sustainability optimization.

Although the proposed conceptual model focuses on the core areas of the industry in terms of its impact and direct or indirect challenges in shifting to DDM through 3DP, limitations still exist in the dimensions covered. This study has yet to evaluate all the disadvantages of 3DP in relation to future technology adoptions, such as product post-processing efficiency in relation to quality control. It also needs to further address the challenges in the localized or distributed manufacturing concept, including involvement from alternative industries, changes expected in legal responsibilities for all stakeholders, the influence of intellectual property protection in various new business structures when using open sources, and an effective approach in human resource management. For the future, the fashion industry also needs to examine alternative DDM technologies and relevant opportunities, such as automated artificial intelligence or robot applications.

This study has opened a dialogue window for the changes forecasted in the era of 3DP. Evidently, the current fashion supply chain as a whole is still undergoing a shift and an acceptance for ongoing technologies, such as the programs that enable 2D digital pattern drafting towards 3D simulation in fit evaluation. Before a full revolution can take place, the industry must make incremental gains and seek niche applications in parallel with the advancements in the technology to establish groundwork. Therefore, it is critical that the fashion fields should keep an open mind in reshaping and reevaluating their existing knowledge in relation to industry training and academic education systems, the interdisciplinary approach to overcoming challenges in a variety of areas, and the exchange of information between industry and academia to allow an efficient transition.

Authors' contributions

LS carried out the review study of the conceptual model integrating 3D printing technology. Both LS and LZ participated in the sequence alignment and drafted the manuscript. All authors read and approved the final manuscript.

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Competing interests

The authors declare that they have no competing interests.

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