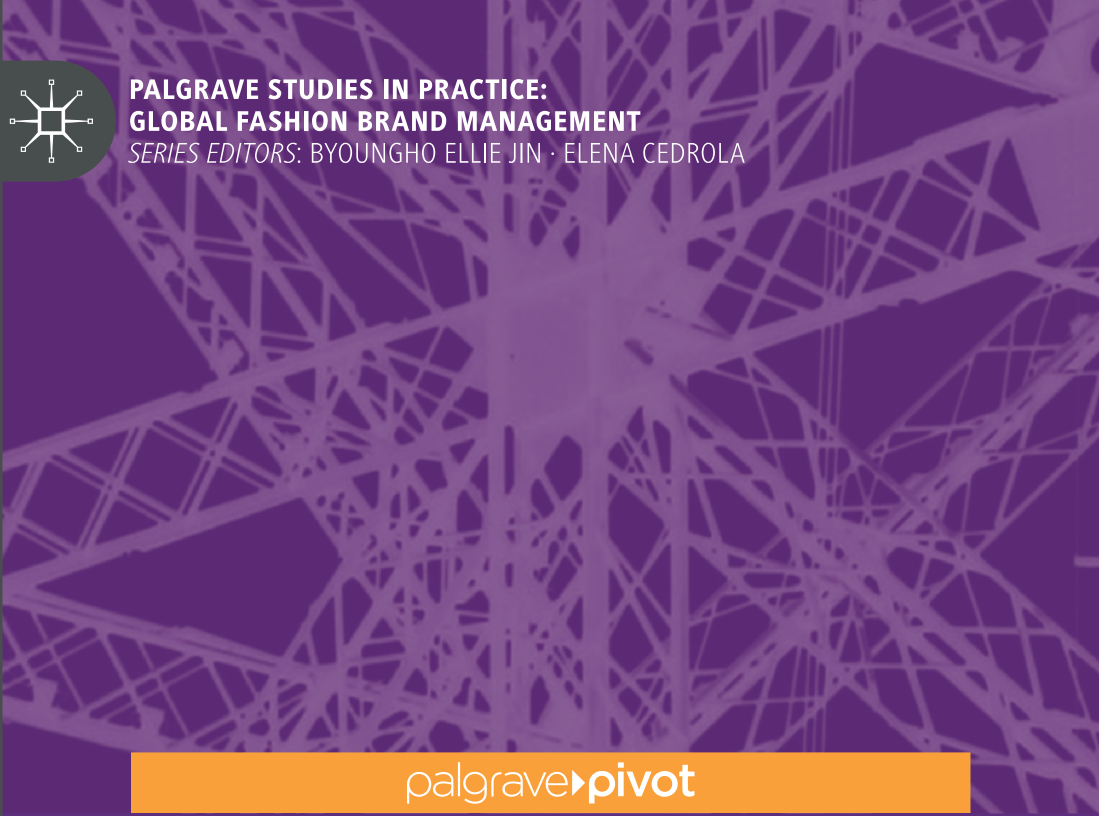

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Leading Edge Technologies in Fashion Innovation

Product Design and Development Process from Materials to the End Products to Consumers

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Preface

The fashion industry has been subject to disruptive changes, having grappled with rising expectations concerning circular fashion and technology innovation. Since the COVID-19 crisis that started in early 2020, the industry's landscape has been transforming at a more vigorous pace, which has accelerated the full integration of leading-edge technologies in various stages of the fashion supply chain. This evolution is not an option anymore, but an unavoidable survival mechanism required to respond to the dynamic business demands during and post the COVID-19 pandemic. Compared to other industries, the fashion industry is still in the process of the full realization of Industry 4.0 with advanced technologies involving artificial intelligence (AI), machine learning, robotics, Internet of Things, 3D printing (3DP), additive manufacturing, augmented reality (AR), and wearable technology. The pandemic bolstered the tangible adoption of such innovation in the fashion industry and the idea of Industry 5.0—collaboration between human beings and machines—is already being discussed. The present disruptive environment compelled fashion companies to rethink the way they operated, which facilitated an overhaul through the integration of a digital platform in their entire supply chain. At the same time, the global movement on sustainability also circled into each stage of the digital fashion supply chain, which has been fostering the current trend of circular fashion.

The objectives of this book are to obtain information regarding the contemporary knowledge on various design and product development-related technologies and their applications in fashion, as well as to envision the future of these technologies to design and engineer apparel-related products. This book is a useful tool for designers, product developers, marketers, and researchers who plan to implement these technologies for the purpose of their work. Each chapter included in this book relates to an aspect of these technologies in fashion-related disciplines, including their development, product design and development, and consumer engagement by utilizing or incorporating the technologies. To demonstrate the application of theory in practice, this book proposes the analysis of cases representing a successful collaboration between innovative technology and fashion in various stages of the digital fashion supply chain. In particular, the book aims to provide current examples of industry or consumer cases in which various technologies have been utilized, which allows the readers to comprehensively understand the ways in which the industry currently implements these technologies during the product design and development process, along with their communication with consumers.

The book is structured in a way that identifies and considers the following four sections: material innovation, innovative technology integration in design and product development, garment automation, and consumer engagement in the fashion industry. After the introductory overview in Chapter 1, Chapters 2 through 7 highlight the emerging practices within the design and product development process, starting from material innovation with technologies (Chapter 1), wearable technology and 3D printing in fashion (Chapters 3 and 4), automation in robotics in garment manufacturing (Chapter 5), and AI in factory operation (Chapter 6) to the end consumer engagement by the means of AR (Chapter 7). Each chapter also explores future trends of technology transformation in the fashion industry. Further, this book outlines a taxonomy of the strategies that emerge due to the association of technology innovation and fashion through case studies that exemplify such strategies.

Chapter 1 introduces technology innovation occurring in the fashion industry, entailing the entire industry pipeline. This introductory chapter provides the theoretical foundation to analyze the cases of innovative technology and fashion collaboration that are presented in the rest of this book. Chapter 2 focuses on two aspects of material innovation: environmental-friendly materials that are utilized in sustainable apparel products and smart textile materials that are capitalized on wearable technology. This chapter covers both academic and industry research by presenting examples of fashion and wearable products that can be created from these innovative materials.

Chapter 3 introduces the currently available wearables in the fashion industry for varied symbolic, aesthetic, cultural, or functional purposes and the projects related to smart clothing and soft wearable robots for future living offering enhanced comfort for the wearer. As 3DP has been rapidly integrated into numerous forefront innovations and explorations in fashion, Chapter 4 introduces a holistic view of the current advancement and prospects of 3DP and additive manufacturing in the fashion supply chain. The chapter also provides insights into the advantages and challenges of 3D CAD and 3DP materials and the interdisciplinary approaches required in adapting and enforcing 3DP innovation. The chapter further showcases the application potentials and values of 3DP in fashion through three prime and practical case studies.

Chapter 5 deals with the general role of garment automation in the fashion industry. It introduces the fundamentals of robotics in fashion and discusses the way it is implemented in garment manufacturing. This chapter also illustrates current automation practices within garment production. The cases employing automated robotic systems are introduced by depicting a few US-based factories presently utilizing robotics in garment production. By foregrounding the fundamental cases of technologies in fashion manufacturing and operation, Chapter 6 aims to enhance the readers' understanding of where the fashion industry stands in relation to AI and provides theoretical points of discussion concerning the areas in which these advances may lead to productivity and sustainable efforts for the industry, both economically and theoretically. Lastly, Chapter 7 discusses the application of AR technology in apparel design by presenting one case of "Plaid Waltz," an innovative design that utilizes AR to amplify the sensory experiences of a plaid dress. This case study provides insights and induces ideas that AR has the potential to implement for designers who are interested in utilizing it.

I hope this book delivers practical insights to companies and academia alike on the integration of leading-edge technology into fashion. By reading this book, I hope readers are able to:

- Holistically depict the entire pipeline of the fashion supply chain, from materials to the end products received by the consumers, which is embedded in the industry cases considered in the book.
- Learn theoretical foundations to explain and justify the collaboration between fashion and innovative technology.
- Learn successful cases of the interaction between fashion and innovative technology to understand how theory and emerging concepts are applied to practice.
- Exhibit an enhanced understanding of how fashion companies assimilate innovative technologies into their processes, predict the implications of such changes, and provide recommendations to the fashion industry.
- Gain a fresh perspective on fashion product innovation and consumer interaction.

I extend my sincere thanks to the authors of each chapter who shared their intellectual expertise and insights with the readers of this book and devoted a substantial amount of their limited time and expressed enthusiasm toward this book. I was fortunate to be supported by all these authors who are also current and emerging leaders in fashion disciplines. I would also like to express my sincere appreciation to Mr. Yu Li and Mr. Mir Salahuddin, the doctoral students at Auburn University, who spent considerable time assisting me with the figure development and (or) cross-checking of the references for all chapters. Finally, I would like to convey my love and gratitude to my family and colleagues who provided limitless support and encouragement on this journey of writing. This is, indeed, the result of them believing in me.

Auburn, AL, USA Young-A Lee

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To my family members, especially dad and mom, who are always with me during my life journey with waves,

To all those who have touched my life and enriched my personal and professional academic journey,

To all those who have provided me endless inspiration, support, and encouragement,

To all living-beings surrounding me!

Young-A Lee

CONTENTS

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List of Figures

CHAPTER 1

Trends of Emerging Technologies in the Fashion Product Design and Development Process

Young-A Lee

Abstract This chapter introduces the technology innovation transpiring in the field of fashion product design and development by covering the entire industry pipeline. As a potentially transformational industry, it is promising that various leading-edge technologies would play a significant role in designing and developing personalized fashion-related products. This chapter provides the theoretical foundation to analyze the cases of the collaboration between innovative technology and fashion demonstrated in the rest of this book. It also delineates the main innovative technologies (e.g., renewable textiles, 3D printing, wearables, robotics, artificial intelligence, augmented reality) currently employed by fashion

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companies, starting from the stage of material development, product design and development, production, to end-consumer engagement. The chapter also deliberates on the future of technology innovation in the fashion industry.

Keywords Technology innovation · Digital transformation · Industrial revolution · Design and product development · Fashion industry

INTRODUCTION

The fashion industry has been subject to rapid changes, having grappled with rising expectations concerning circular fashion and technology innovation. Since the COVID-19 crisis that started in early 2020, the industry's landscape has been transforming at a more vigorous pace, which has accelerated the full integration of leading-edge technologies in various stages of the fashion product development pipeline. This evolution is not an option anymore, but an unavoidable survival mechanism required to respond to the dynamic business demands during and post the COVID-19 pandemic.

Compared to other industries, the fashion industry is still in the process of the full realization of the fourth industrial revolution (Industry 4.0), which is a cyber-physical systems revolution with advancements in technologies involving artificial intelligence (AI), machine learning, robotics, Internet of Things (IoT), 3D printing (3DP), additive manufacturing, virtual/augmented reality (VR/AR), and wearables (See, 2019). The pandemic bolstered the tangible adoption of such innovation in the fashion industry and the idea of the next industrial revolution (Industry 5.0) is already being discussed, which is essentially the interaction and collaboration between human beings and machines (Vollmer, 2018). The industry will be kept evolving with the next level of industrial revolution from time to time and we should be ready to be onboard in this disruptive change through product and process innovation.

Two volumes of the book series in practice on global fashion brand management written by Jin and Cedrola (2018a, 2019) have covered the concept of product and process innovation in the fashion industry and presented various cases of product and process innovation occurring in the fashion supply chain. According to Jin and Cedrola (2018b), innovation is “the development of new products, production processes, business practices or forms of organization” (p. 2) and product innovation in textiles and clothing sectors occurs at three levels in materials, styles, and product development (p. 5). Jin et al. (2019) state that “process innovation is a new or significantly improved way of doing things in a business that typically increases production levels and decreases costs” (p. 2). To reach both product and process innovation in the fashion supply chain, technology innovation plays a significant role in each stage of the industry pipeline.

Considering this era of disruptive transformation that we have encountered in the fashion industry and society (Bendoni et al., 2015), businesses and consumers’ priorities are shifting; however, the lack of investment in those emergent technology innovation fails to fully meet the rising demand. Thus, this chapter discusses technology innovation in fashion product design and development, covering the entire industry pipeline by introducing the key innovative technologies (e.g., renewable textiles, 3D design, 3DP, wearable technology, robotics, AI, AR) used across processes, ranging from material development, product design and development, and garment production to end-consumer engagement. The chapter also discusses the future of technology innovation in the context of circular fashion.

Technology Innovation in the Circular Fashion Industry

Material Innovation

During the wave of a global pandemic, fashion companies demonstrated that sustainability, bettering the planet and people, remains a top priority and digital technologies are the means by which companies can leverage fashion brands to manufacture products more sustainably (Sourcing Journal, 2021). For instance, companies are cutting back on single-use plastic by investing in renewable energy and the protection of biodiversity. Patagonia, the outdoor apparel company, by partnering with Infinited Fiber Company (IFC), actively advocates textile circularity with the utilization of fibers made from textile waste (Friedman, 2021). IFC focuses on the scalability of its technology implementation as a part of the bold movement of textile circularity (TextileExchange, 2020). This circularity movement has been escalating, reinforced by several other companies. The LYCRA Company's COOLMAX® and THERMOLITE® EcoMade fibers, made from 100% textile waste, exemplify textile circularity (The LYCRA Company, 2021). TENCEL™ cellulosic fibers are also a part of nature's cycle, provided that they are compostable and biodegradable, and thus, completely eco-friendly (Tencel, 2021). Other examples of sustainable alternative fibers with lower environmental impact (e.g., soy, bamboo, eucalyptus, stinging nettle) were showcased in Jin and Cedrala's study (2018b, pp. 7–8).

Leading fashion companies have explored the development of sustainable fashion products, utilizing biomaterials out of plants' byproducts. Miomojo, a premier Italian fashion brand, sells luxurious plant-based leather bags made from natural materials, such as apple peels and cores, cactus, and corn (Hannon, 2021a). Mycelium, derived from fungi such as mushrooms, is also one of the sustainable materials increasingly adopted as a leather alternative (Hannon, 2021b). Adidas' latest concept shoe, Stan Smith Mylo$^{\text{tm}}$, is one such example (Adidas, 2021). Gucci's Dementra is a new animal-free luxury material containing more than 77% plant-based materials, including viscose, wood pulp, and bio-based polyurethane (Chua, 2021). Another example is Nike's use of pineapple leather in its new sustainable sneakers (Binns, 2021). These emerging sustainable products are the outcomes of efforts in material innovation that have duly considered their impact on ecosystems. An increasing number of future-forward sustainable materials will shortly be developed, considering the increasing popularity and adoption of textile circularity. This movement has already been escalated by technology advancements and the shift in consumers' interest from fast fashion to circular fashion.

Product Design and Development

Product innovation in textiles and clothing sectors occurs at three levels in materials, styles, and product development (Jin & Cedrola, 2018b, p. 5), and process innovation is "a new or significantly improved way of doing things in a business that typically increases production levels and decreases costs. Such innovation might come in the form of new processes or techniques, new equipment, or new software" (Jin et al., 2019, pp. 2–3). Technology innovation is a key player in the product design and development process in the current digital transformation era. Jin et al. (2019) well provided the overview of process innovation during product development by implementing various technologies such as 2D computer-aided design/manufacturing (CAD/CAM), 3D garment simulation, and big data and deep-learning algorithms (pp. 8–11). The following parts present the current implementation of various 2D and 3D technologies in the product design and development process since then and discuss the urgent needs to nurture the next generation of workforce.

The fashion industry is exhibiting an increasing involvement in connecting the virtual world to the physical one. For instance, Optitex provides an integrated 2D/3D platform that facilitates the quick creation of realistic 3D digital garments, which empowers apparel and soft goods companies to revolutionize the way they develop, produce, and market their products (Optitex, n.d.). In July 2019, Alvanon announced a new collaboration with Under Armour to inspire fashion brands to embrace 3D virtualization (Alvanon, 2019). They collaborated to develop new 3D tools, particularly working with 3D avatar size sets, to create better products with enhanced sizing and standardization. In August 2019, Tukatech opened its library of over 750 virtual fit models for all the global brands, retailers, and 3D users in the fashion industry, intending to help the industry establish the foundations for digital development (PR Newswire, 2019).

Numerous companies, including Target, have already turned into 3D virtualization of products to reduce the time and cost of product design and development and to minimize physical sampling. The author of this chapter witnessed the company's realization of the commitment to implement 2D/3D programs (e.g., Optitex, CLO, Browzwear) in their product design and development process over the last decade. The PI (Product Innovation) Apparel Conference held in Los Angles in February 2018 also revealed to the author the fashion industry's rigorous experiments with 2D to 3D conversion in its daily activities of pattern-making and prototyping. At the conference, industry presenters articulated the need for 3D sample makers/operators/creators who could precisely understand the foundations of pattern development and garment fit. They urged for academic institutions to equip next generation workforces to work in a digitally revolutionizing industry. It is time for fashion educators to work together with industry professionals and build the talent pipeline—the next generation of fashion creators who can comfortably reorient themselves from operating with 2D to working with 3D.

Garment Production

Compared to the application of digital technology in the product design and development stage of the fashion industry, its utilization in garment production (e.g., additive manufacturing, automation with robotics) is still in the early development and/or adoption phase. Considering that automation with robotics is the main trend in other industries, the fashion industry must align with this movement, despite the complexities of its implementation at the garment production level.

The fact is evident by this enlightening statement, "The smart factory is a digitally enabled manufacturing facility in which the physical production process is fully integrated with a supporting digital technology ecosystem" (Stomp et al., n.d., p. 4). Garment production implements various digital technologies of Industry 4.0, including IoT, AI, machine learning, additive manufacturing, data integration, and robotics to digitize manufacturing operations, linking the entire production process. This digital transformation would eventually facilitate automation in the garment production line.

Micro-factory

The concept of micro-factory or on-demand production, the current focal point in the fashion industry, responds to the societal pressure that emphasizes sustainability and digital transformation, along with the consideration of consumers' demands on customization and personalization. At the Texprocess event in 2019, the MICROFACTORY, coordinated by the Deutsche Institute fur Textilund Faserforschung (DITF) and partnered with industry, showcased a fully integrated production chain from design to finishing (DITF, n.d.). Recently, the British garment manufacturer, Fashion-Enter Ltd., which partnered with Zund UK, demonstrated a sustainable micro-factory concept in London, utilizing digital cutting technology and advanced workflow processes (Textile World, 2021). The company already partnered with Kornit Digital for garment printing and customization. Further, its on-demand garment manufacturing efforts enable fully automated digital cutting with minimal manual intervention (Images, 2021). Another example, Amazon's automated on-demand clothing factory, was introduced in Jin et al.'s (2019) study, stating as "The entire process of apparel production—from printing textiles and cutting patterns to sewing—is automated with minimum human supervision" (p. 11).

Automation with Robotics

Automation in garment production facilitates on-demand garment manufacturing. The application of robotics also fosters automation in this manufacturing process. Sewbots by SoftWear Automation is a good example that revolutionized the fashion supply chain, promoting on-demand, made-to-measure production (SoftWear Automation, n.d.). However, compared to other industries, automation with robotics in garment production is still limited. Most sewing robots currently available in the market are capable of producing simple products, such as t-shirts, but are not advanced enough to produce sophisticated garments. The success of automation with robotics in garment production relies on the way fashion manufacturers can seamlessly integrate this advanced technology with other digital technologies (e.g., AI, additive manufacturing, CAD) in production facilities. Skilled 3D operators, who have acquired fundamental knowledge on apparel pattern-making principles, should be entrusted with managing these automated facilities.

3D Printing and 3D Fabrication

Advancements in 3D printing, also referred to as additive manufacturing, enable the fashion industry to incorporate this technology into the on-demand manufacturing process to create personalized and customizable wearables, considering circular fashion. 3D printing has been much utilized in producing fashion accessories, such as shoes, bags, and jewelry, which has proven the scalability of 3D printed fashion accessories for commercialization. For instance, Adidas introduced the first mass-market 3D printed shoe, called Futurecraft 4D, in 2017, in which the midsole was printed with light and oxygen using the Carbon Digital Light Synthesis™ technology developed by a company called Carbon (Sanger, 2017). This concept upgraded to ADIDAS 4D within two years, showcasing the potential of data-driven design and digital manufacturing on a global scale (Adidas, 2019). Other examples include Julia Daviy's sustainable 3D printed bag and jewelry collections (Daviy, n.d.).

At the moment, the majority of 3D printed garments have been created through selective laser sintering (SLS) with nylon or fused deposition modeling (FDM) with other rigid filaments, for example, Nervous System's (2014) kinematics dress and Kim et al.'s (2019) 3D printed dress. Most 3D printed wearables are composed of rigid hinge-joint interfaces or interlocked chainmail (e.g., Chen, 2020; Nervous System, 2014, 2017), resulting in limited flexibility compared to apparel made from traditional textiles. Although designers started adopting flexible 3D printing materials, such as thermoplastic polyurethane (TPU) in wearables' design (e.g., Cui & Sun, 2018; Sun, 2018), its application has been limited to small pieces of wearables, such as bras and gloves.

In 2017, Danit Peleg, the founder and creative director of 3D Printed Fashion, launched a revolutionary platform on her website allowing customers to order personalized 3D printed jackets (Peleg, 2018a). She also offers the digital files of the 3D garment, supplied to customers who can print their garments using their 3D printer (Danit Peleg, 2018b). Nervous System's kinematics cloth also enables the creation and purchase of custom-fit 3D printed garments, reflecting one's body shape, garment shape, pattern density, and textile structure (Nervous System, n.d.). The use of 3D printing has also expanded to luxury fashion brands such as Atelier Versace and a high-end jewelry company American Pearl (Jin & Cedrola, 2018b, p. 23).

3D printing is revolutionizing the fashion industry by enforcing the adoption of circular fashion through the disruption of the traditional fashion supply chain. Research and development are encouraged for developing 3D printed wearables with its material innovation, which can fully mimic garments made of traditional fabrics in terms of functionality and wearability.

Consumer Engagement and Experiences

The disruptive nature of the fashion industry movement has allowed consumers to digitally engage in the product design and development process, which better fulfills their demands through the features that enable customization, personalization, and virtual try-on. Advanced technologies, such as AI, machine learning, AR, and VR in the era of Industry 4.0, have enhanced consumer engagement and enriched their experiences with wearables (Rahman, 2019). Fashion brands utilize AR technology for different purposes, including fashion shows and consumer try-on experiences with the help of smart mirrors (PYMNTS, 2019; Zadidi, 2018). For the past few years, AR technology has rapidly evolved in both traditional and online fashion retail platforms to better engage with consumers. The COVID-19 crisis has underscored the relevance of AR technology for online fashion retailing because of its capability to allow consumers to experiment with different fashion products without visiting physical retail stores. However, its applications in apparel design and development have not been widely explored. Integrating AR technology in wearables is a novel way of digital product creation, which enables the wearer to better communicate with other people and try on products by utilizing their multiple sensory system (Min & Kim, 2019).

Wearable technology, part of product innovation according to Jin and Cedrola (2018b), is also employed to increase consumer engagement and experiences with products for the purpose of improving their health and well-being. Consumers often consider Google glasses, Apple Watch, Fitbit, and Bluetooth headsets as wearable products (Gartner Inc., 2017). Although smart clothing or smart footwear is one type of wearables integrating information technology and wearable computing devices, they are still at an early adoption stage in fashion. Followings are a few examples of smart clothing that were introduced in Jin and Cedrola's (2018a, 2018b) work on innovations in product development (pp. 24–25): Tommy Hilfiger's solar-powered jacket, Ralph Lauren's smart shirt with PoloTech™, Under Armour's athlete recovery sleepwear, and Levi's Strauss & Co's smart commuter jacket partnered with Google. Wearable technology, one of the promising technologies to promote human beings' needs and desires, requires substantial research and development on smart or e-textiles, smart clothing, and wearable robots with the holistic integration of other advanced technologies, such as AI, machine learning, and AR to thrive in the new digital landscape.

Conclusion and Future Trends

The fashion industry has been rapidly interrupted by the COVID-19 crisis, owing to country-wide lockdowns, factory shutdowns, travel bans, unavailability of labor, raw material shortages, soaring logistics costs, retailer and supplier bankruptcies, and a surge in online demand. All these factors compelled the companies in the industry to rethink the way they operated, which facilitated an overhaul through the integration of a digital platform in their entire product design and development process. The global movement on sustainability also circled into each stage of the fashion supply chain, which has been fostering the current trend of circular fashion.

This introductory chapter discussed technology innovation that has emerged at each stage of the fashion supply chain, including material development, product design and development, production, and consumer engagement in the context of circular fashion as shown in

Fig. 1.1. In the current state of industrial revolution (Industry 4.0), this chapter depicted the prevailing uptakes of technology innovation occurring in renewable materials, wearable technology, 3D visualization and prototyping, 3D printing, on-demand micro-factory, automation with robotics, customization and personalization, and consumer engagement through AR and VR, which helps minimize the time to market, reduce costs and waste, and improve efficiency. This technology innovation will be continuously evolving throughout the forthcoming industrial revolution process.

Scalability is one of the key challenges concerning the complete integration of emerging technologies. To scale its capabilities, the current barriers, including process, culture, and talent, should be revisited.

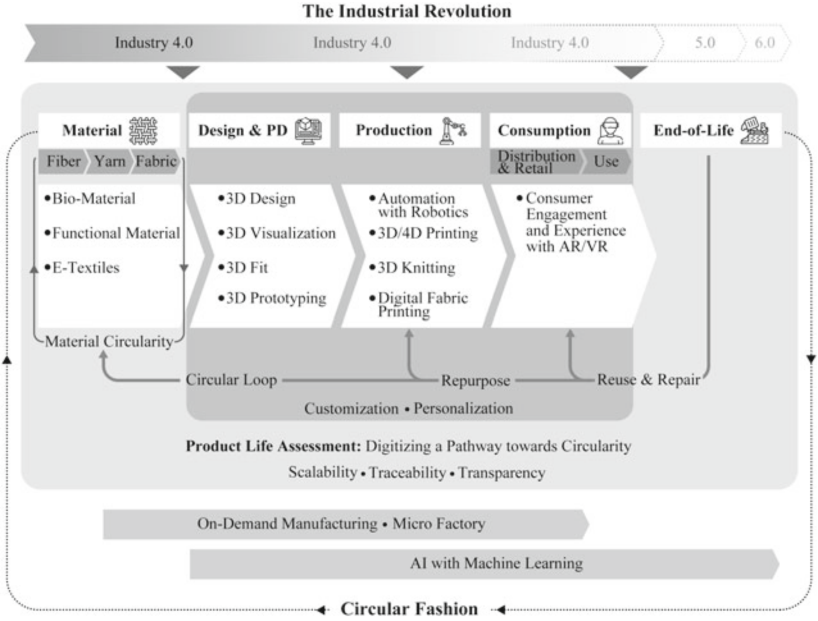

Fig. 1.1 Technology Innovation throughout the Circular Fashion Pipeline (*Source* Developed by the author)

Existing supply chain models cannot function with the disruptive innovations evolving with the current digital fashion industry movement (Just-Style Magazine, n.d.). The future of fashion supply chain should comprehensively reflect the disruptive innovations and consumer demands during the process of product design and development. Transparency, traceability, and collaboration are the key assets for the industry success. The COVID-19 pandemic has been a decisive turning point in this industry, enabling its accommodation to the digital transformation movement. For instance, Calik Denim addresses the incorporation of sustainability, transparency, and digitalization, through the QR code integrated system, which shares the lifecycle assessment (LCA) scores of the products calculated with 8 parameters. In addition, the system allows the tracing of fiber origin, certificates, and other vital and relevant information (Warren, 2021).

Over the last decade, the need for workforces with a fresh and productive blend of skills, possessing production floor experience and skills in advanced digital technologies, has gradually become apparent. The upscaling of workforces in the fashion industry in terms of talent is thus highly encouraged. Fashion programs around the globe can play a major role in nurturing agile workforces through close collaboration with industry partners. People working in various sectors, including academia, design and development, manufacturing, retailing, and supply chain, should be familiar with emerging terms and definitions (e.g., 3D operator, material designer, digital global footprint) utilized in the digital landscape of the fashion industry. Workforces in the digital and circular fashion industry need to be more flexible to work as a cross-functional team to better align with the course of direction of the industry. A new industrial revolution will continually evolve and, thus, everyone should be ready for constant disruptive changes.

Sources of Further Information

For additional information and news regarding technology innovation in the fashion industry, please reference the following collection of resources.

- Add Ease LLC (https://www.addease.nyc/): A full-service 3D apparel and technical design agency.

- Artistic Denim Mills (ADM; http://admdenim.com/index.php): A company that seeks to introduce innovation and unique market solutions throughout the value chain in the denim industry to produce premium denim fabrics and garments for high-end customers.
- Browzwear (https://browzwear.com/): A company providing 3D fashion design, development, and merchandising solutions.
- CLO (https://www.clo3d.com/): A virtual fashion simulation company revolutionizing the design process with true-to-life 3D garment simulation.
- Fashion Enter (https://www.fashion-enter.com/): A non-profit social enterprise striving to be a center of excellence for the sampling, grading, production, and learning and development of skills within the fashion industry.
- Kalypso (https://kalypso.com/): A Rockwell Automation company focusing on the digital transformation of the value chain, from product to plant to end user.
- Lectra (https://www.lectra.com/en): A company empowering customers through industrial intelligence. Their software, hardware, and services build agility and efficiency into every process, from design to production.
- MOTIF (https://motif.org/): An apparel knowledge hub that connects professionals around the world with the skills and industry expertise they need to transform their businesses, lives, and careers.
- Nervous System (https://n-e-r-v-o-u-s.com/): A generative design studio that works at the interaction of science, art, and technology using 3D printing technology. They create computer simulations to generate designs and use digital fabrication to realize products.
- Optitex (https://optitex.com/): A company providing end-to-end fashion design software for various industries including fashion.
- PI Apparel (https://apparel.pi.tv/): A membership community for apparel and footwear professionals which helps to adapt and thrive in a digital world.
- Seamless Design Solution (http://www.seamlessdesignsolutions.com/): A company helping fashion apparel companies to become more cost effective, agile, and sustainable through virtual technology.
- Self-Assembly Lab (https://selfassemblylab.mit.edu/): A research lab at MIT inventing self-assembly and programmable material technologies.

- STITCH 3D (https://www.stitch3d.com/): A software as a service startup helping fashion product creators to scale 3D collection development.

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CHAPTER 2

Material Innovation with Technologies

Huantian Cao

Abstract The development of innovative materials used in fashion and other wearable products can help improve the environment and the quality of human life. This chapter focuses on two aspects of material innovation: (a) environment-friendly materials that are used in sustainable apparel products and (b) smart textile materials that are used in wearable technology. Environment-friendly materials include materials made from renewable sources and waste, that are easily biodegraded or recycled, and made from inherently benign feedstock. Smart textile materials are textiles that have a variety of sensing capability and can improve human health and comfort. This chapter covers both academic and industry research. Examples of fashion and wearable products made from these innovative materials are discussed.

Keywords Material innovation · Smart textiles · Sustainable · Function

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Introduction

The innovative development of textiles and other materials for producing wearable products has played a significant role in the history of human civilization. The production and uses of cotton, silk, and flax textiles in the ancient world, the machinery production of textiles in the first industrial revolution (Industry 1.0), and the invention of nylon that synthesized polymer for textile application from small molecules in the 1930s are a few examples of important technology milestones related to textile innovation. Presently, there are numerous innovative materials used in fashion and other wearable products that help improve the environment, human health, and the quality of human life.

Global textile fiber production has doubled in the past two decades to 107 million metric tons in 2018. Approximately 62% of this quantity (about 66.6 million metric tons) was comprised of synthetic fibers (Textile Exchange, 2019). A vast majority of synthetic fibers are produced using petrochemicals derived from depleting resource petroleum as feedstock and are not biodegradable. The production, use, and disposal of synthetic fibers cause a major environmental impact, resulting from resource depletion and harmful solid waste ending up in landfills. There have been material innovations in recent years to solve the resource depletion and solid waste problems involving apparel and other wearable products. Smart textiles can detect environmental conditions or external stimuli, such as light, temperature, pressure, mechanical or magnetic effects, chemicals, and electricity, and generate adequate responses as a consequence of the external stimulus (Khattab et al., 2018). In the past two decades, there have been countless innovations in smart textiles, which can be further applied to develop smart clothing and other products.

This chapter focuses on two aspects of material innovation: environment-friendly materials and smart textile materials. Environment-friendly materials include materials created from renewable sources and waste or from materials that can be readily biodegraded. Smart textile materials include textiles that have sensing capability and functional textiles that are equipped with self-cleaning capability and other functionalities.

Environment-Friendly Materials

Materials Made from Renewable Resources and Waste

Traditional materials used in apparel and footwear are naturally occurring materials extracted from plants or animals, such as cotton, flax, and wool, or synthetic materials, such as polyester and nylon. In recent years, there have been material innovations that involve fabricating materials by the means of microorganisms, such as bacteria and fungi. These are natural materials and can multiply with appropriate and sufficient nutrients; thus, they can be considered as materials derived from renewable resources. Countless agricultural and industrial wastes, as well as wastes from consumer products, such as used cotton t-shirts and wool socks, contain organic matters, including cellulose, protein, and lignin, that can serve as nutrients in the microorganism growth. This provides an opportunity to utilize waste in material development.

A mycelium-based composite consists of a natural reinforcement or filler, such as hemp fibers, and the mycelium of a fungus (Lelivelt et al., 2015). When mushroom (fungi) mycelium grows, a network of branching hyphae binds the nutritive substrate consisting of biomass to create a vast three-dimensional matrix (Yang et al., 2017). This natural fungal growth process uses agricultural and industrial waste, such as rice hulls, wheat straws, flax hurds, and cotton fibers, in the form of the nutritive substrate required to develop fully biodegradable composites from renewable resources and waste (Jones et al., 2020).

Fungus *Ganoderma sp.* (Reishi mushroom), cotton plant biomass (e.g., cotton carpel, cottonseed hull), and other nutrients, such as starch and gypsum, were used to develop mycelium composites that can be applied as molded packaging material (Holt et al., 2012). Pelletier et al. (2013) developed mycelium composites, which have an acoustic absorption property similar to that of traditional foam for insulation boards application, using agricultural byproducts, such as switchgrass, rice straw, sorghum stalks, flax shive, kenaf, and hemp. Lelivelt et al. (2015) grew fungi *Coriolus versicolor* (Turkey Tail mushroom) and *Pleurotus ostreatus* (Oyster mushroom) on plant-based substrates, including hemp hurd, hemp fibers, hemp mat, and wood chips, to develop mycelium biocomposites and evaluated the materials' compressive strength. It was found that the combination of nonwoven hemp mats and the strain *C. versicolor* exhibited the densest mycelium growth. Further, the compressive strength at

10% deformation of the best mycelium composite was between 24 and 93 kPa (Lelivelt et al., 2015).

Jiang et al. (2014, 2017) used woven textile fabrics (100% jute burlap and 100% linen cloth) and agricultural waste pre-colonized with mycelium to develop mycelium composite laminate and sandwich parts that can function as shoe soles. Silverman et al. (2020) used four mushroom species, namely *Pleurotus ostreatus* (oyster), *Pleurotus citrinopileatus* (yellow oyster), *Pleurotus eryngii* (king oyster), and *Ganoderma lucidum* (reishi) to develop mycelium composites. Further, chicken feathers, flour, husk psyllium reishi, and recycled textile fiber mat were also used for the purpose. The mycelium composite made from the king oyster species had a mean compressive strength of 340 kPa, which is higher than the maximum walking pressures of both young and old adults. This indicates that the composite is appropriate for shoe sole application (Silverman et al., 2020). Using the mycelium composite as the middle sole, a pair of shoe prototypes were designed and developed (Tang et al., 2018).

Ecovative Design, LLC (Green Island, NY, USA) has developed and commercialized mycelium-based products. Their products include the mycelium composite packaging product Mushroom® packaging, which is compostable, and the 100% mycelium product MycoFlex™, which can be used as a leather substitute and insulating foams for gloves, apparel, and footwear products.

Cellulose can be synthesized by a variety of bacteria, such as *Acetobacter xylinum*, through four key enzymatic steps using glucose as the carbon source: (a) phosphorylation of glucose by glucokinase, (b) isomerization of glucose-6-phosphate (Glc-6-P) to glucose-1-phosphate (Glc-1-P) by phosphoglucomutase, (c) synthesis of UDPglucose (UDPGlc) by UDPG-pyrophosphorylase (UGPase), and (d) synthesis of cellulose via synthase reaction (Lee Buldum et al., 2014). Several industrial wastes, including agro-industrial waste (e.g., corn stalk, citrus peels, coffee cherry husk), brewery and beverage industrial waste (e.g., makgeolli sludge produced in traditional rice wine distilleries, waste from beer fermentation broth), sugar industries, pulp mills, and lignocellulosic biorefineries waste (e.g., sugarcane molasses, water-soluble fraction from pulping waste liquor), textile mills waste (e.g., cotton textile waste), and other industrial waste (crude glycerol, flour-rich waste streams, and sunflower meal hydrolysates), can be used as the nutrient source for bacterial cellulose production (Hussain et al., 2019). Bacterial cellulose is an ultrafine pellicle/sheet structure comprised of cellulose filaments, with ribbons of width 30–50 nm and thickness 4–5 nm, which have novel properties, including high crystallinity (80–90%) and degree of polymerization (4,000–10,000 anhydroglucose units), high water absorption and holding capacity (up to 100 times of its own weight), superior tensile strength (100–160 GPa for a single fiber, comparable to steel or Kevlar®), good biocompatibility, resistance to chemical and heat shock, lack of toxicity, easy sterilization, and selective porosity (Hussain et al., 2019).

Lee, Xiang et al. (2014) developed bacterial cellulose fiber mats using green tea, granulated cane sugar, white vinegar, and commercial organic SCOBY (symbiotic culture of bacteria and yeast). To overcome the loss of tensile strength and increased softness due to the easy moisture absorption of the bacterial cellulose fiber mats, Nam and Lee (2019) bonded the bacterial cellulose fiber mats with denim and hemp fabrics to develop a multilayered cellulosic material. They found that the multilayered cellulosic material's heat and moisture transfer properties (evaporative resistance, total heat loss, permeability index, evaporative potential) and mechanical properties (break force) were better than or similar to a two-layered calf and pigskin leather, indicating that the material can be used as a leather alternative in fashion products such as shoes. Chan et al. (2018) developed two tailor-shaped cultivation techniques, contacting surface-blocking cultivation and panel-shaped cultivation, to produce bacterial cellulose sheets that have garment panel shapes. Using these bacterial cellulose sheets, they developed a zero-waste short-sleeved shirt prototype without the pattern cutting process.

Biodegradable and Recyclable Materials

There are three types of polyesters: (a) linear chain aliphatic polyesters, which are relatively biodegradable but have low mechanical property; (b) aromatic polyesters, which have enhanced mechanical properties but are relatively less biodegradable; and (c) aliphatic–aromatic copolyester, which have balanced mechanical and biodegradable properties from both aliphatic and aromatic polyester classes (Satti & Shah, 2020).

Polylactic acid (PLA) is an aliphatic polyester synthesized through condensation polymerization or ring-opening polymerization using lactic acid as the starting material (Drumright et al., 2000). Lactic acid can be produced through the bacterial fermentation of a carbohydrate derived from plants, such as corn, sugar cane, sugar beet, and cassava (Barrett, 2020); thus, PLA is made from renewably resourced feedstock. It can be completely biodegraded after 40 days under composting conditions with a temperature of 60 °C (Drumright et al., 2000). Lee, Kim et al. (2014) compared the biodegradation of PLA nonwoven fabrics by three enzymes (lipase, esterase, and alcalase) and found that alcalase was the most effective enzyme to degrade PLA, resulting in 25% weight loss after 21 days and 100% tensile strength loss after 14 days. PLA has been industrially produced since NatureWorks LLC (Minnetonka, MN, USA) commercialized it in 2003. The global production of PLA is around 240,000 tonnes per year. From that amount, around 135,000 tonnes are produced by NatureWorks LLC under the brand name Ingeo™, and approximately 75,000 tonnes are produced by Total-Corbion (Gorinchem, The Netherlands) under the brand name Luminy® (Barrett, 2020). The applications of Ingeo™ PLA include packaging, plastics, and textile fibers for nonwoven materials, apparel, and home textile products.

Banerjee et al. (2016) developed aliphatic polyester poly(3-hydroxybutyrate) (PHB) through a mixotrophic biosynthesis process followed by polymer extraction by utilizing the cyanobacteria (blue-green algae) *Nostoc muscorum*. The expected applications of the extracted PHB polyester in the fiber or yarn form include textile medical products, such as tissue scaffolds, sutures, and surgical meshes (Banerjee et al., 2016). In 1998, BASF (Ludwigshafen, Germany) commercialized an aliphatic-aromatic copolyester poly (butylene adipate-co-terephthalate) (PBAT) under the trade name Ecoflex® (Morro et al., 2019; Witt et al., 2001). After 22 days of degradation by actinomycete *Thermomonospora fusca* isolated from the compost material, more than 99.9% of Ecoflex® had depolymerized to monomers, namely, 1,4-butanediol, terephthalate, and adipate (Witt et al., 2001). Younes (2020) used branched aliphatic–aromatic copolyester made by the BASF to develop textile yarns with a range of different values for shrinkage, tenacity, elongation, modulus, and abrasion properties to suit the agricultural, horticultural, and other non-traditional textile applications. The BASF also produces a blend of 55% PBAT and 45% aliphatic polyester PLA under the trade name Ecovio®, which exhibited biodegradability at an accelerated pace than Ecoflex® when bacterium *Bacillus subtilis* was present (Morro et al., 2019). Ecoflex® and Ecovio® are used in carrier bags, compostable can liners, mulch film, and food wrapping (BASF SE, 2008). There have not been any commercial fashion products made from these two biodegradable polyester materials.

Novotný et al. (2015) synthesized aromatic-aliphatic copolyesters (PETP/LA) by solvolysis of poly(ethylene terephthalate) (PETP) with water solutions of lactic acid (LA) and the subsequent condensation polymerization of the reactive products. Though scanning electron microscopy revealed that micromycete *Aspergillus fumigatus* and yeast *Candida guilliermondii* broke PETP/LA fibers, the biodegradation of PETP/LA by bacterial, yeast, and higher-fungal organisms was not efficient, as only 5–10% mass reduction was observed after 6 weeks of the degradation experiment (Novotný et al., 2015).

Smart Textile Materials

Textile-Based Sensors

Textile can serve as a substrate for a variety of sensing technology. Textile-based sensors are soft, flexible, and comfortable and can easily and seamlessly integrate into wearable products. Textile-based sensors that can convert a physical deformation, such as strain and pressure, to electrical (resistive or capacitive) signals can be utilized to monitor human movements and physiological parameters for developing smart clothing (Atalay et al., 2017; Liu et al., 2017; Seyedin et al., 2019). Essentially any textile material, such as cotton, polyester, nylon, and rayon, and any structure, such as fiber, yarn, and fabric, can be used as the textile substrate for deformation sensor development (Bashir et al., 2014; Lee et al., 2019; Liu et al., 2017). Since electrical signals are measured, a conductive material, such as carbon nanotube (CNT) (Lee et al., 2019; Liu et al., 2017), graphene (Yang et al., 2018), and silver nanoparticle (Lee et al., 2018), is coated on the textile substrate through in-situ chemical polymerization, vapor-phase polymerization, dip-coating, spray coating, roller coating, and rod coating for sensor development (Seyedin et al., 2019).

A few important performance parameters of strain sensors include stretchability or sensing range, sensitivity or gauge factor (GF), linearity, hysteresis, and cyclic stability (Atalay et al., 2017; Seyedin et al., 2019). GF is the amount of resistance or capacitance change over applied strain; hysteresis is observed when at a specific strain in a cyclic deformation, the sensing signal in stretching is different than that in relaxation; cyclic stability refers to the ability of the sensing response to return to its original value after the removal of strain and the ability of the sensor to exhibit similar sensing response at various cycles (Seyedin et al., 2019).

The linearity between resistance or capacitance change and strain is crucial for the calibration process of a sensor (Atalay et al., 2017). A high-performance sensor should offer a substantial sensing range, high GF, low hysteresis, high linearity, and good cyclic stability.

Resistive textile strain sensors have been extensively investigated. When the textile is stretched, the resistance of the textile could be increased or decreased, which can be used as the sensing signal. An increased resistance results in a positive GF, and a decreased resistance results in a negative GF. Yang et al. (2018) dip-coated graphene oxide (GO) on polyester knit fabric and then reduced GO sheets to graphene sheets to develop strain sensors. Due to the structural difference in the y-direction (wale) and x-direction (course), the sensor exhibited different stretchability, sensitivity, and cyclic stability in the two directions: a maximum GF of −26 in the strain range of 8% and 500 stretching/releasing cycles of 5% strain in the y-direction and −1.7 GF in the strain range of 15% and 500 stretching/releasing cycles of 7.5% strain in the x-direction (Yang et al., 2018). Lee et al. (2019) used a spray layer-by-layer technique to coat single-walled CNT on a 90% nylon and 10% polyurethane knit fabric and developed resistive textile-based strain sensors. The textile strain sensor exhibited high stretchability of 100%, high GF of 72 at 100% strain, and over 1,000 stretch-and-release cycles (Lee et al., 2019). Lee et al. (2018) coated silver nanoparticles on polyurethane multifilament fibers to develop highly sensitive sensors (~659 GF), having an ultra-broad sensing range (200% stretching) with excellent durability (10,000 stretching cycles).

Compared with the resistive textile strain sensors, capacitive textile strain sensors have high linearity, low hysteresis, and long cyclic stability, but they have relatively low sensing range and low sensitivity and are more difficult to fabricate since they require two conductive textile electrodes and a dielectric layer (Seyedin et al., 2019). Atalay et al. (2017) developed capacitive textile strain sensors by utilizing highly stretchable silver-plated knit fabric (Shieldex Medtex-130) as the electrode and silicone elastomer as the dielectric. The sensors exhibited a high sensing range with 100% strain, a high linear relationship ($R^2 = 0.999$) between the strain and capacity, low hysteresis (1.5% for 100% strain), and a GF of 1.23 (Atalay et al., 2017).

In addition to strain, pressure can also cause electrical property changes, such as a change in resistance and capacitance. Therefore, similar conductive textile materials can also be utilized in the fabrication of pressure textile sensors. Using resistive textile pressure sensor as an example, the sensitivity of the pressure can be defined as follows:

$$S = \frac{(\mathrm{R1} - R0)/R0)}{P1 - P0}$$

where S denotes the sensitivity, R0 and R1 denote the resistance before and after the application of pressure, respectively, and P0 and P1 denote the corresponding pressure applied before and after (Tian et al., 2019).

Liu et al. (2017) fabricated two-layer resistive textile pressure sensors using Ni (nickel) coated polyester/nylon textile as the bottom interdigitated textile electrode and single-walled CNT coated cotton textile as a top bridge. An increased external pressure would increase the contact area between the top CNT textile bridge and the bottom Ni textile electrode, resulting in increased current (or decreased resistance). The textile pressure sensor exhibited a high sensitivity of 14.4 kPa^{-1} for pressure below 3.5 kPa and a sensitivity of 7.8 kPa^{-1} for pressure between 3.5 and 15 kPa, good cyclic stability of 1000 cycles, a fast response time of 24 ms, and a low detection limit of 2 Pa (Liu et al., 2017). Doshi and Thostenson (2018) used an electrophoretic deposition (EPD) method to coat polyethyleneimine (PEI) functionalized CNT on nonwoven fabrics made from natural (wool) or synthetic (aramid) fibers and developed textile pressure sensors with an ultrawide sensing range from 0.0025 to 40 MPa. The sensors exhibited a sensitivity (GF) of about 0.05 MPa^{-1} (or 5×10^{-5} kPa^{-1}) and good linearity at low pressure but became nonlinear at higher pressures (Doshi & Thostenson, 2018).

Functional Textiles

Self-cleaning textiles, which clean themselves without any substantial physical assistance, can be classified into three categories: (a) physical self-cleaning (the lotus effect similar to rolling rain droplets in lotus leaves due to the hierarchically rough and hydrophobic surface); (b) chemical self-cleaning (the degradation of stains on fabric); and (c) biological self-cleaning (killing bacteria on textile and prevent their growth) (Ashraf et al., 2016). Out of the three categories, chemical and biological self-cleaning textiles can be considered as smart textiles.

Semiconductors, such as TiO_2, ZnO, Fe_2O_3, CdS, WO_3, SnO_2, and ZnS, can function as photocatalysts to oxidize and degrade organic compounds when exposed to light (Wang et al., 2015). Incorporating nanoparticles of these semiconductor photocatalysts into textile substrates through coating or electrospinning presents an opportunity to develop self-cleaning textiles that have health, environmental, and military applications (Bedford & Steckl, 2010; Wang et al., 2015). Among these semiconductor photocatalysts, TiO_2 and ZnO have been the most widely investigated in self-cleaning textile development. TiO_2 and ZnO nanoparticles can kill bacteria through the reactive oxygen species (ROS) mechanism (ROS degrading DNA, RNA, and proteins) in the presence of ultraviolet (UV) light (Nguyen et al., 2019). Therefore, textiles treated with TiO_2 and ZnO nanoparticles can possess both chemical and biological self-cleaning functions. In addition, TiO_2 and ZnO nanoparticles can block UV rays to provide UV protective function for textiles (Tsuzuki & Wang, 2010).

Ashraf et al. (2016) grew ZnO nanorod on polyester fabric and then modified the fabric with hydrophobic chemical octadecyltrimethoxysilane (ODS) using a vapor deposition method. The fabric showed all three types of self-cleaning properties: hydrophobic performance of 158° water contact angle (physical), removal of the color of C.I. acid blue 9 stain (chemical), and the inhibition of the growth of bacteria *S. aureus* and *E. coli* (biological) (Ashraf et al., 2016). Zhu et al. (2017) coated ZnO nanoparticles on cotton fabrics using a traditional dip-pad-dry-cure process to develop self-cleaning and UV blocking textiles. The fabric could degrade and remove the color of methylene blue (MB) under light irrigation and had an ultraviolet protection factor (UPF) of > 100 (representing $> 99.99\%$ UV absorption). It also exhibited good self-cleaning durability and wash fastness: removing MB stains after three consecutive degradation cycles and washes (Zhu et al., 2017).

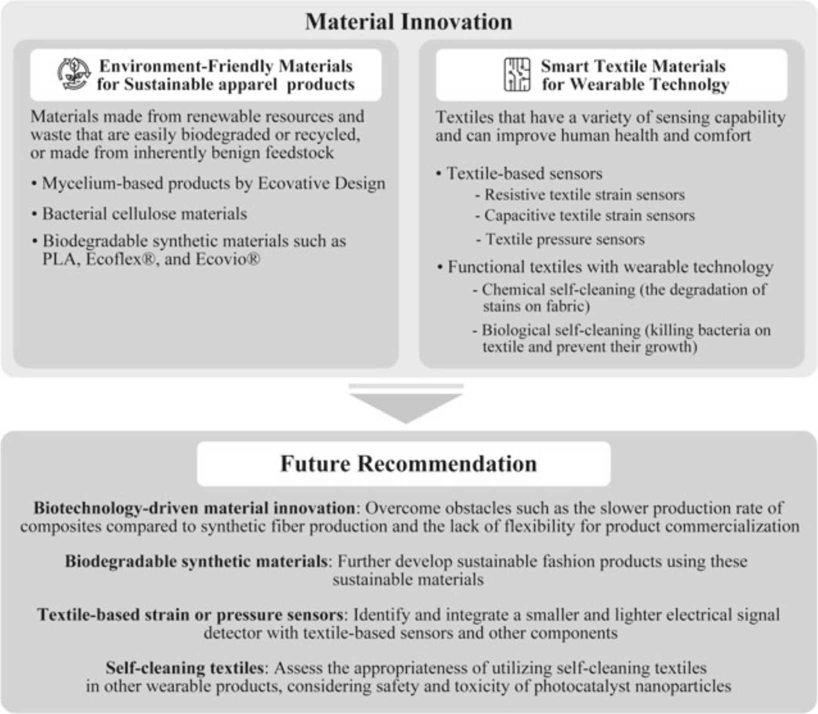
Dognali et al. (2016) coated nanosized TiO_2 film on a 100% cotton fabric through a dip-coating process that has chemical and biological self-cleaning properties. They observed that under solar simulator illumination, the fabric can degrade and discolor tea stains after 2 hours, and inactivate 99.9% of bacteria *E. coli* and *S. aureus* after 20 and 30 minutes, respectively. Zhou et al. (2017) coated two types of TiO_2 nanoparticles, i.e., pure TiO_2 and polyvinyl alcohol (PVA) modified TiO_2, on polyamide 6 (nylon 6) fabrics. Both types of TiO_2 nanoparticles coating could introduce chemical and biological self-cleaning, UV protection, and surface superhydrophobility properties to the nylon 6 fabric. It was observed that the performance of PVA modified TiO_2 nanoparticles coating was better than that of TiO_2 nanoparticles coating. PVA modified TiO_2 nanoparticles coated nylon 6 fabric demonstrated 5 consecutive cycles of degradation and discoloration of methyl orange stains, 99% anti-microbial rate against bacterium *S. aureus* under visible light, a UPF value of 1233, and water contact angle of 154.6° (Zhou et al., 2017).

Conclusion and Future Trends

This chapter discussed material innovations of environment-friendly materials and smart textiles. The environment-friendly materials that have been discussed in this chapter include materials made from renewable resources such as waste and biodegradable materials. These material innovations intend to solve the resource depletion and solid waste problems caused by synthetic textiles, which account for approximately 62% of all textile fiber production (Textile Exchange, 2019). The biotechnology-driven material innovations discussed in this chapter, such as mushroom mycelium composites and bacterial cellulose, are mainly occurring in academic research. Future research should aim at overcoming obstacles such as the slower production rate of composites compared to synthetic fiber production and the lack of flexibility (Fernandes et al., 2019; Lee, Xiang et al., 2014; Silverman et al., 2020) for the commercialization of these materials in apparel and footwear. Biodegradable synthetic materials, such as PLA, Ecoflex®, and Ecovio®, have been commercially produced. PLA textiles have been used to produce apparel products by Chinese sporting goods brand Xtep (Business Wire, 2021) and Japanese sustainable fashion brand Ecomaco (Nagano, Japan). In the future, the development of sustainable fashion products using these materials, especially Ecoflex® and Ecovio®, needs to be explored further.

Textile-based strain or pressure sensors have been tested by attaching them to human skin to assess their capability to detect human motion and physiological signals such as pulse (Liu et al., 2017; Yang et al., 2018). Smart wearable prototypes, such as smart gloves that can monitor finger bending, have also been developed (Lee et al., 2018). These academic studies typically measured the electrical signals in sensor characterization by means of a benchtop electrometer (Lee et al., 2018; Liu et al., 2017; Yang et al., 2018), which affected the wearability of the textile-based sensors. In the future, a smaller and lighter electrical signal detector should be identified and integrated with the textile-based sensors and other components (e.g., battery), for the purpose of incorporating the entire sensing system into a wearable product.

During the COVID-19 pandemic, there has been an increased demand for self-cleaning textiles that can degrade chemicals and kill viruses and bacteria. The company Trajet (France) developed self-cleaning velvet fabrics that can annihilate the coronavirus when brought under UV light and can be utilized in metro trains to ensure safer public transportation (Vivent, 2020). Further research, including safety and toxicity of photocatalyst nanoparticles, is essential to assess the appropriateness of utilizing these self-cleaning textiles in other wearable products such as face masks. Summary of material innovation with technologies and future recommendation for its use is summarized in Fig. 2.1.



Material Innovation

Environment-Friendly Materials for Sustainable apparel products

Materials made from renewable resources and waste that are easily biodegraded or recycled, or made from inherently benign feedstock

- Mycelium-based products by Ecovative Design
- Bacterial cellulose materials
- Biodegradable synthetic materials such as PLA, Ecoflex®, and Ecovio®

Smart Textile Materials for Wearable Technolgy

Textiles that have a variety of sensing capability and can improve human health and comfort

- Textile-based sensors
  - Resistive textile strain sensors
  - Capacitive textile strain sensors
  - Textile pressure sensors
- Functional textiles with wearable technology
  - Chemical self-cleaning (the degradation of stains on fabric)
  - Biological self-cleaning (killing bacteria on textile and prevent their growth)

Future Recommendation

Biotechnology-driven material innovation: Overcome obstacles such as the slower production rate of composites compared to synthetic fiber production and the lack of flexibility for product commercialization

Biodegradable synthetic materials: Further develop sustainable fashion products using these sustainable materials

Textile-based strain or pressure sensors: Identify and integrate a smaller and lighter electrical signal detector with textile-based sensors and other components

Self-cleaning textiles: Assess the appropriateness of utilizing self-cleaning textiles in other wearable products, considering safety and toxicity of photocatalyst nanoparticles

Fig. 2.1 Summary of Material Innovation with Future Recommendation (*Source* Developed by the book editor)

Sources of Further Information

- BASF Ecoflex® (https://plastics-rubber.basf.com/global/en/performance_polymers/products/ecoflex.html): A website including the information of Ecoflex®, a biodegradable material aliphatic–aromatic copolyester poly(butylene adipate-co-terephthalate) (PBAT), produced by BASF.
- BASF Ecovio® (https://plastics-rubber.basf.com/global/en/performance_polymers/products/ecovio.html): A website including the information of BASF's biodegradable material Ecovio®, which is a blend of 55% PBAT and 45% aliphatic polyester PLA.
- Ecomaco (https://www.superdelivery.com/en/do/dpsl/205100/): A wholesale website that sells PLA apparel products manufactured by Ecomaco. Its official website is https://ecomaco.com/.
- Ecovative Design LLC (https://ecovativedesign.com/): A pioneering company in the development of mushroom mycelium composite materials.
- NatureWorks LLC (https://www.natureworksllc.com/): A company producing Ingeo™, a renewably resourced aliphatic polyester polylactic acid (PLA).
- The Ingeo™ Journey (https://www.natureworksllc.com/~/media/News_and_Events/NatureWorks_TheIngeoJourney_pdf.pdf): A document describing the raw materials, production, and environmental benefits of Ingeo™.
- Total-Corbion (https://www.total-corbion.com/): A company producing Luminy®, another brand of polylactic acid (PLA).

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CHAPTER 3

Wearable Technology in Fashion

Sumin Koo and Youngjin Chae

Abstract As smart clothing is being increasingly recognized as a strong contender in future wearables, with its flexible and comfortable interface becoming more accessible to people, fashion also has been successfully orienting itself as the next game-changer in wearable technology through its connection to a wide range of design, lifestyle, and functionality with its scalability. This chapter introduces the currently available wearables in the fashion industry for varied symbolic, aesthetic, cultural, or functional purposes and the projects concerning smart clothing and soft wearable robot for future living with the enhanced comfort of the wearer. The chapter also discusses the future of wearable technology in the fashion industry.

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Keywords Wearable technology · Wearables · Smart clothing · Wearable robotics · Soft robot

Introduction

The growing demands of an enriched quality of life have led the current technology to establish multi-communication channels between human beings and the environment. Innovative technology has made our life ubiquitous by digitally connecting humans with various services and advanced paradigms, such as the Internet of Things (IoT). Wearable computer is an electronic device system that monitors the user and the surrounding environment of the user's body. To enable the users to perform productive functions while providing them with information, comfort, or appeal, wearables are designed to be worn or carried by the wearer for extended hours during their daily activities. Over the past decade, wearable technology has continuously evolved with enhanced intelligence, performance, mobility, and improved design.

In recent years, wearables have demonstrated their market potential through a few well-known products, including smartwatches or chest bands (International Data Corporation, 2020). Smart clothing and wearable robots have been recently recognized as the future vanguards of wearables, given their potential to seamlessly connect physical and digital functionalities. By providing an interface that can be worn on the body for an extended period, these systems aim to significantly enhance user capabilities and comfort through intimate, personal, and practical solutions which relate to a wide range of users' lifestyles to a great extent. As the next generation of wearable systems emerges, this chapter shares the definitions, types, development stages, current trends, and the potential emergence of smart clothing and wearable robots.

Smart Clothing

Smart clothing is a smart system created by integrating wearable technology into a garment platform, aiming to seamlessly connect the user with the ubiquitous environment (Park & Jayaraman, 2003). Compared to other types of wearables, smart clothing emphasizes clothing as a unique environment indispensable to human life that is utilized at all places and times. It is also being recognized as an ideal platform that could leverage the intimate interaction between the wearer and the intelligent ambient system unconsciously (Mann, 1996). To seamlessly close the gaps present between the human body and the ubiquitous environment, the recent trend of smart clothing focuses on developing tangible interfaces with enhanced usability and comfort during its daily use, considering the wearers' demands and lifestyle.

Definitions and Types of Smart Clothing

Smart clothing is a novel garment system that detects signals, processes information, and actuates responses to provide interactive reactions. It senses and communicates the wearers' physical and environmental conditions by responding to electrical, thermal, mechanical, chemical, magnetic, or other forms of stimuli (Tao, 2001). It is a wearable computing system that connects its functional components to the clothing platform, which could be realized by transforming the electronic components into textile materials (Cho, 2009). As it is operated through IT-based applications (Cho, 2006), smart clothing is also often referred to as digital clothes (Ji & Lee, 2009). There are five main components in smart clothing, including interfaces, communication components, data management components, energy management components, and integrated circuits (Tao, 2005).

Initially, the application of smart clothing was often classified by the purposes it served in body monitoring, entertainment, and information communication (Cho, 2009), in the four areas of sports, healthcare/medical, fashion/entertainment, and military/public (McCann & Bryson, 2009). In 2020, Muhammad Sayem et al. also discussed application areas of smart clothing, such as health, wellness, fitness, and social engagement based on the literature review. Further, its applications in the other emerging areas were also discussed. The three emerging application areas are: (a) healthcare and wellness, (b) sports and advanced protection, and (c) emotional comfort and social engagement.

Healthcare and Wellness

Health monitoring system and wellness is a promising market for smart clothing to seamlessly monitor the user's vital biosignals for an early diagnosis of critical symptoms with on-time prevention. With a unique platform that can leverage the full body engagement and effortless interaction, a new solution for remote healthcare and wellness control is expected to be provided to the aging population (Poon et al., 2017). Electrocardiogram (ECG), electroencephalography (EEG), electromyogram (EMG), breathing patterns, sweat, or temperature are common and useful biometrics that can serve as a health enabler when monitored by the smart clothing system (Fernández-Caramés & Fraga-Lamas, 2018). Compared to other health monitoring wearable devices that are positioned around the body to perform their respective functions, smart clothing is considered as an amalgamation of different components on a singular macro garment layout, without disrupting the functions of individual components, capacities, or user comfort (Chen et al., 2016). A product range of smart clothing for healthcare and wellness, covering various functions and consumer groups (AiQ, 2017), varies; examples include socks to detect diabetes (Siren, 2020) or a baby hat to prevent sudden infant death syndrome (Neopenda, 2016).

Sports and Advanced Protection

For the purposes of clothing ranging from athletic wear, military, and firefighter uniforms, to space suits, different functional supports can be implemented to enhance or protect the user in various circumstances through the smart clothing system. The wearers' conditions, comprising of their movement, location, or health status, can be analyzed by assessing the environmental conditions, which are detected in terms of heat, moisture, vapor, pressure, strain, and chemical or visual variables data to prevent accidents and injuries to users who require extra support or protection in different occasions.

Emotional Comfort and Social Engagement

Smart clothing is now being recognized as a tangible platform that could provide emotional and social comfort to the wearer as they go about their daily life. This includes the interpretation of different emotions resulting from the change in garment design by utilizing smart materials as a novel way of communication (Lifetech Wear, 2019; Sensoree, 2021). To this extent, aesthetical fashion and entertainment are important application areas for smart clothing, which has a large potential distribution network with its scalability. As smart clothing has been indicated as an ideal interactive platform to collect and communicate an abundance of personal and social data for various end uses, major fashion brands, including Nike, Adidas, Under Armour, and Levi's, are currently developing core hardware and acquiring the know-how pertaining to digital product development at an accelerated pace.

Developments in Smart Clothing

One of the early stages of smart clothing is often attributed by the wearable computer launched in 1960, a cigarette pack-sized device with 12 transistors that was worn to beat the Las Vegas casinos (Thorp, 1998). Between the 1970s and the 1990s, Steve Mann attempted designing wearable computers and soon came to be known as one of the pioneers in wearable computing (Mann, 1996, 1997a, 1997b). After Mann claimed in 1997 that smart clothing would be the future interface of wearable system, a smart shirt was academically reported by the Georgia Institute of Technology to monitor vital signals for healthcare and battlefield applications in the late 1990s (Gopalsamy et al., 1999). The smart clothing prototypes were launched in 2000 by Reima as the Cyberia survival suit (Shishoo, 2005). To monitor the physical conditions and the position of the wearer in Arctic environments, the suit was fashioned from fabric embroidered with a GPS receiver, sensors, and electrodes.

The commercial wearable garment was revealed in 2000 by Philips and Levi's, who collaboratively blurred the boundary between the fashion and electronic domains (Marzano et al., 2000). This was also the commercialized electronic textile-based (e-textile) garment system where the electronic devices were placed inside the pockets. However, due to the bulky and rigid nature of the components, coupled with their primitive level of technological feasibility, it was challenging to mass commercialize it. In 2006, Zegna Sports incorporated textile-based sensors to the iJacket as a fabric keypad to be connected with an external mobile device (Ji & Lee, 2009). Several fashion brands have endeavored to develop smart clothing. For instance, Levi's has introduced a new jacket with a gesture-sensing cuff to detect different movements as a new interacting panel with the use of conductive threads and e-textiles to simplify the manufacturing processes and commercialize the costs of the final product (Kumar et al., 2019).

Smart clothing that embeds wearable technology into a garment structure can be classified by different definitions and parameters of wearable smart systems that enable interaction between the user and the environment. This part introduces three different categories: (a) the integration level of technology into wearables, (b) the location level of wearables, and (c) the intelligence level of smart systems.

The Integration Level of Technology to Wearables

Technical Commission 124 of the International Electrotechnical Commission (IEC), which is responsible for the standardization of wearable technologies, has classified wearables into four types: accessory, textile/fabric, patchable, and implantable (IEC, 2019). Smart clothing is categorized under textile/fabric wearables. It is considered advantageous since it interacts with the user and the environment for an extended period. Owing to the high integration level of the electronic components over a significantly large surface level, smart clothing often reports higher energy consumption compared to other accessory types, including smartwatches, smart glasses, or fitness trackers, that reflect low energy consumptions.

The Location Level of Wearables

Wearables have been further classified by the IEC Standardization Group 10 as near-body, on-body, or in-body wearables according to their location, distance, and contacted area of the user body (IEC, 2019). Similarly, it can be categorized based on the virtual or physical means of human body extensions: prosthetic, handheld, wearable, or implanted types (Uğur, 2013). In most cases, smart clothing system can be defined as the physical range of wearables in combination with virtual extension, where IoT and digital connection play a major role.

The Intelligence Level of Smart Systems

Intelligence was divided into three categories based on the level of communication and exchange of information through the interaction between the human and the environment by the means of textiles (Tao, 2001). Compared to smart systems that passively sense the environment, active or very smart systems sense to react, or sense and adapt to provide intelligent solutions in different circumstances.

Developmental Trends in Smart Clothing

To seamlessly support and monitor the daily activities of the wearer, technical feasibility, performance, capacity, safety, connectivity, and power are typically considered as the main parameters of the smart clothing system. Recently, the user experience and acceptance also have been garnering significant attention to leverage the overall performance of the smart clothing system. Efforts are also being directed toward the structural and aesthetical design and scalability of the electronic components by considering the cost, the manufacturing process, and commercialization of the smart clothing materials.

E-textiles

Advanced materials and structures that can sense the wearer's surrounding conditions are considered crucial elements of smart clothing innovation. As one of the first inventions by mankind and the key material in the conventional clothing industry, textiles are being recognized as the ideal material space where the innovative technology around the user can be realized. E-textiles are an advanced way of integrating conventional electronics with sensing functionality onto flexible fabrics through mechanical modifications (Castano & Flatau, 2014). Since its first example in 1883, the initial developments of e-textiles were driven by a series of discussions in academia during the 1990s to monitor health signals and body movements (Hughes-Riley et al., 2018). In the 2000s, e-textiles for switches, keyboards, power generators, and communication were developed to support the user interaction with different stimuli in life. However, e-textiles should be convenient, comfortable, washable, highly reliable, and durable to be fully embedded within clothing effectuate wearable 2.0 (Muhammad Sayem et al., 2020).

As integration of technology into a larger interface of the final system critically affects the user's mobility and comfort, the technological practicality of e-textile components by making them smaller and flexible has become one of the prime considerations, along with the capacity and performance of the smart module. A conventional power unit based on a conventional lithium-ion battery of the smart clothing system is known as one of the heaviest and bulkiest components, which limits the user experience of the all-day carry-on device. E-textiles for renewable energy harvesters and storage have been gaining attention as an alternative, sustainable power device to run the smart system with improved comfort for the wearers (Chae et al., 2013; Shi et al., 2020). Advanced geometry, design, and manufacturing solutions in e-textiles have also been actively discussed to achieve enhanced performance, comfort, and sustainable competitiveness in the market. This includes the approaches driven from the use of aesthetical components (Chae et al., 2015), textile structure (Liu et al., 2017), digital manufacturing system (Jost et al., 2013), and modularization of e-textile materials.

Wearability in Smart Clothing

Wearability is the interaction between the human body and the wearable object in which the extent of its dynamic depends upon the movement of the human body (Gemperle et al., 1998). The first useful guideline of wearability was suggested based on 13 parameters for designing comfortable, manageable, and unobtrusive wearable products by considering the body in motion. The form that wearables appear in can also be established by incorporating all the human aspects of smart clothing (Cho, 2006), namely, comfort, fashion, durability, and safety, in them. This can be achieved by integrating usability and functionality of electronic devices, comfort and fashion that are characteristics of clothing, and finally, safety and durability to create the most ideal wearables. Recently, the wearable acceptability range (WEAR) scale for smart clothing was introduced and validated (Kelly, 2016; Nam & Lee, 2020).

Sustainable Market Development of Smart Clothing

Quantifying the market value of smart clothing is challenging, as it typically reflects the anticipated value rather than accounting for the advanced materials that are in the process of developing and will potentially be utilized in the production of smart clothing, altering its actual market value later. The standardization of innovative technology is essential for a sustainable market growth of smart clothing which can be initiated by promoting its technological development through positive competition, lower production costs, and the eventual establishment of consumer trust in the market (Ji & Lee, 2009). Arguments have also been made in favor of the digital manufacturing system (Seyedin et al., 2020; Uzun et al., 2019) and circular economy (Chae & Hinestroza, 2020) while bridging the knowledge gaps among various stakeholders (Lifetech Wear, 2019) for smart clothing and textiles.

Wearable Robots

Wearable robots are expected to enhance muscle strength and facilitate body movements, provide safety by preventing accidents or injuries, and enhance stability, endurance, and productivity. The number of people with musculoskeletal issues is increasing as the population ages and consequently, the demand for wearable robots is soaring. The wearable robot market is expected to expand rapidly, at a CAGR of 42.6% between 2020 and 2027 (Market Research Future, 2021). These kinds of wearable robots can provide people with more working opportunities, enable them to increase their involvement in social activities, and help them gain independence by engaging in their daily lives without commuting to hospitals. Such advantages will lead to enhance the quality of human life and well-being.

In Industry 4.0, wearable robots are the most essential technologies for the lives of individuals. The wearable robotic field combines other leading technologies of the future, such as artificial intelligence (AI), big data, virtual reality (VR), augmented reality (AR), new materials, energy innovation, 3D and 4D printing, and the Internet of Things (IoT). Numerous existing wearable robots, such as exoskeletons or exo-suits, were made of stiff and heavy materials, which are uncomfortable to wear. People usually prefer wearable robots that are lightweight, flexible, soft, durable, thin, easy to wear and remove, easy to use and care for, and safe (Koo, 2018). Thus, recently, wearable robots have become more lightweight, flexible, intelligent, accurate, faster, and softer. This development makes wearable robots more human-friendly and comfortable to wear. Further, they are equipped with enhanced functions for the users.

Definitions and Types of Wearable Robots

Wearable robots are body-worn robots that can detect their wearers and the environment for the purpose of assisting, treating, or improving the wearers' body movements. Such robots monitor human body movements and the state of the environment. They accumulate data through sensors, analyze them by utilizing connected computers or microprocessors, and operate actuators that move or control the mechanisms and the systems.

Wearable robots can be classified into the following categories: industrial, military, rescue, medical and treatment, sports and entertainment, and education. Most existing wearable robots deliver power to enhance muscle strength and movement of heavy-duty industrial workers and military personnel or assist and treat the movements of elderly and disabled people in their daily lives. Trials have experimented with wearable robots for entertainment applications, such as VR games, sports, and services for the elderly, as well as for educational purposes. However, people preferred utilizing wearable robots for daily activities rather than for special occasions (Koo, 2018). It is vital to develop wearable robots for the public to assist the individuals' normal movements in their daily lives.

Based on the item types, wearable robots are also called exoskeletons, exo-suits, soft wearable robots, or smart clothing. Exoskeletons and exo-suits usually provide more power and precise control, but they are typically bulkier, larger, heavier, and stiffer than soft wearable robots. Their users are primarily heavy-duty industrial workers, military personnel, and disabled people. They can be cumbersome to wear and remove and might limit the wearer's natural movements. They can potentially cause musculoskeletal injuries and friction burns and bruises on the skin due to the stiff nature of the material and its heavy weight.

Soft wearable robots are made of soft and flexible materials, such as silicone, thermoplastic polyurethane (TPU), and fabrics. These materials are increasingly taking the form of clothing-type wearable robots and smart clothing fabricated with a higher proportion of flexible materials, such as fabrics. These garments enhance comfort and diminish the perceived risks of use, but their performance power is inferior in comparison with exoskeletons and exo-suits. Thus, if exoskeletons and exo-suits can enhance muscle strength, soft wearable robots can assist muscle strength. Disadvantages of soft wearable robots include weak support and issues pertaining to washing and care; however, related technologies, such as materials, batteries, sensors, and actuators, continue to improve. Thus, soft wearable robots are expected to become as powerful and easy to care for. Some soft wearable robots have begun resembling clothing; smart clothing. They provide enhanced comfort with socially acceptable styles that enable people to wear them in daily life.

Wearable robots can also include bio-implemented devices that can replace body parts, such as arms and legs. These usually mimic the human body in appearance or are covered with artificial human skin. These kinds of wearable robots approach the wearers' perception of their own body and enable speedy reactions to their intentions to move. However, issues related to regulations, safety, and complexity in replacing human body parts, persist.

The Development of Exoskeletons and Exo-suits

Early developments in wearable robots were mainly dominated by exoskeleton and exo-suits designed from stiff materials, such as metal frames, large motors, and pneumatic actuation sources. In 1890, Nicholas Yagn patented a wearable system to aid a wearer while walking, running, and jumping. There were large bow-shaped supports that were donned from the shoulders to the feet and wraps to cover the waist, thighs, and knees, connecting the supports (Yagn, 1890). In the 1960s, General Electric developed Hardiman, which was built as a joint project of Army-Navy, that resembled a large robot arm. It could carry about 1,500 pounds and make it feel like 60 pounds (General Electronics, 2016). In the 1990s, Cyberdyne initiated a research project to develop a Hybrid Assistive Limb, with its prototype being developed at the University of Tsukuba to assist the elderly and the disabled in their daily lives (Bender, 2014). In the 2000s, the Pentagon's Defense Advanced Research Projects Agency researched exoskeletons for military soldiers (Freedberg, 2019). In 2004, a research team at the University of California (UC), Berkeley developed the Berkeley Lower Extremity Exoskeleton, with which a wearer could lift 200 pounds (Bender, 2014). The Human Universal Load Carrier (HULC) and Lockheed Martin manufactured the wearable robots developed at UC Berkeley (Bender, 2014).

In the 2010s, myriad exoskeleton-type walking-assistive wearable robots were developed worldwide. Japan's Honda Group developed a walking-assistive exoskeleton that can support a wearer's weight while walking or ascending the stairs (Honda, 2020). Along similar lines, RB3D developed various versions of the Hercule exoskeleton, which integrated electronic motors and assisted wearers to move faster with less muscular power (Army Technology, 2012). In 2013, the HAL was continuously developed and the fifth generation of HAL was certified for use, which weighed about 22 pounds (Bender, 2014). This exoskeleton was intended for medical and industrial purposes and included models designed for the whole body or just the lower body. The US Department of Defense researched Tactical Assault Light Operator Suit for future solider uniforms including wearable helmets with AR and heads-up displays (Magnuson, 2019). LIG Nex1 in South Korea has been developing exoskeleton robots since 2010 for their soldiers (Army Recognition, 2020).

Like soldiers, firefighters also usually wear heavy protective equipment, such as the oxygen tank, which can limit their movements and tire them quickly. Thus, the Korea Institute of Industrial Technology has been developing a hydraulic-powered exoskeleton robot (HyPER) since 2008 and introduced HyPER for firefighters (Won, 2015). A team at UC Berkeley developed the SuitX exoskeleton for people with paraplegic paralysis, attempting to make it affordable and lightweight and to produce less heat (Colliver, 2016). SG robotics of South Korea introduced the WalkON exoskeleton suit, which employed pneumatic actuators. It also could be connected to AR glasses used to control the wearable robot (Yoo, 2017). In 2017, a Chinese company, Fourier Intelligence, developed the Fourier X1 exoskeleton for gait assistance of people who had suffered a stroke and spinal cord injuries. This exoskeleton was made of aluminum and carbon fiber integrated plastic plates (Marinov, 2017).

In the late 2010s, LG electronics introduced CLoi SuitBot, which assists industrial workers' lower body muscular strength. This exoskeleton is a part of LG CLoi's robot series in 2018 (LG Newsroom, 2018). Similarly, in 2019, Hyundai Motor Group debuted VEX, which is intended for industrial workers who are required to stand and lift their arms over their heads, such as automotive factory workers who must drill in such a manner (Hyundai, 2019). VEX can be worn with the help of shoulder straps, like a backpack, and is fastened with buckles on the chest and waist. The supportive legs can be worn by attaching them to the thighs and the knees. The wearer can sit on the device which also functions as a portable chair (Hyundai, 2019). The length can be adjusted with an allowance of 18 cm. It has 6 strength stages (Hyundai, 2019). In the same year, Samsung Electronics introduced the Gait Enhancing and Motivating System (GEMS) exoskeleton type as part of its Samsung Bot series. Samsung Electronics removed inessential links and details to provide the GEMS outfit with a clean, simple shape (Samsung Newsroom, 2019). GEMS can enhance muscle strength by around 20% and increase the walking speed by 10% (Kim & Kim, 2019).

These exoskeletons and exo-suits enhance and assist muscle strength to a greater degree than wearable robots and smart clothing. Exoskeletons and exo-suits have continued to evolve. They have become smaller, thinner, more lightweight, more flexible, and easier to wear and remove. Further, they have an extended battery life and exhibit enhanced performance levels. Further developments intended to enhance the ease of wear and comfort are expected in the future.

The Development of Soft Wearable Robots and Smart Clothing

To make wearable robots more comfortable and easier to use in daily life, researchers in recent years have formulated methods to make them lightweight, flexible, and soft. For instance, trials were conducted to develop fabrics that incorporate shape memory alloy (SMA), which can automatically change their length and shape. In 2015 and 2016, the Fashion Design and Technology Lab at UC Davis developed SMA fabrics and fabricated the Enfold jacket, which can automatically close fasteners for people with movement disorders (Lin et al., 2015) and the Fleurtech dress, which automatically alters garment lengths utilizing SMA and micro servo-motors (Lee et al., 2016). NASA has been developing wearable robots for astronauts. In 2018, they developed and presented soft wearable upper extremity garments with the aid of a cable transmission system (Whiting, 2018).

The Harvard University's Biodesign Lab has researched various wearable robots and worked on developing soft wearable robots that incorporate fabrics and soft stretchable sensors. In 2019, a soft wearable robot was developed which can decrease energy consumption by 9.3% while walking and 4.0% while running (Kim et al., 2019). In the same year, the Korea Institute of Machinery and Materials developed a jacket-type wearable robot that combined the SMA springs and integrated fabric artificial muscles that could adjust in length. This jacket, mostly made of fabrics, such as normal cloth, was intended to support its wearers in lifting objects (Park & Park, 2019).

NASA and General Motors developed the Robonaut robotic glove by the means of pressure sensors, actuators, micro-controllers, and a lithium battery, intending to support the palm and enable industrial workers and astronauts to grab objects more easily (Technical Textile, 2016). Cho's research group at Seoul National University developed the washable Exo-Glove Poly, which is a flexible glove that utilizes wires and motors (Kang et al., 2019; Lee et al., 2017). It was designed for people with movement-related complications or disorders of the hands and fingers. Bae's research group at UNIST also developed the Feel the Same flexible gloves, which were made of fabrics (Kim et al., 2018). These gloves can recognize hand movements in real time and project these movements on a computer. The gloves can also vibrate, which can be used with games (Kim et al., 2018). BioServo in Sweden introduced gloves attached to a chest harness made of fabrics and straps. These gloves allow the wearer to work more powerfully with their hands; they were intended for industrial workers, elderly people, and others who work extensively with their hands.

Since 2017, Konkuk University, Ajou University, and Chung-ang University in South Korea have collaborated to develop pants-type wearable robots utilizing SMA wires and Teflon tubes incorporated into stretchy fabrics. These robots shorten the length of SMA wires attached to the ankles to assist in lifting the wearer's heels while walking (Kim et al., 2020). More than 90% of garments were produced from flexible fabrics and were designed to look like a normal cloth that can be worn for regular use.

A team of engineers at Vanderbilt University developed a wearable robot in the form of a connected vest and shorts that utilized stretchable bands and springs to protect the muscles of the back and the waist of the wearers who suffer from back pain, such as surgeons and nurses (Hall, 2017). These devices are mostly made of flexible fabrics and can be operated with a smartphone. At Seoul National University, Han and Ahn (2017) fabricated SMA threads and knitted them by adjusting their knit and purl arrangements to create knits that moved differently. Similarly, the Wearable Technology Lab at the University of Minnesota developed active compression clothing with the help of SMA wires of variable lengths (Eschen et al., 2018). The compression clothing could control the contractions and expansions because of the SMA wires.

In 2018, an interdisciplinary collaborative research group from Seoul National University, Chung-Ang University, Konkuk University, the Korea Research Institute of Standards and Science (KRISS), and the Korea Institute of Science and Technology (KIST) developed a flexible arm sleeve designed from stretchable fabric, flexible sensors, and micromotors to provide active compression for moving arms (Yang et al., 2019). To make wearable robots flexible and soft, it is imperative that the sensors and actuators are flexible and soft. Thus, ample studies have endeavored to incorporate sensors into fabrics, and recently, there also has been a shift toward the incorporation of actuators into fabrics. Park's research group at Seoul National University invented flexible, lightweight fabric-based sleeves that can assist arm movements, such as twisting, by the means of pneumatic was employed to cut the fabrics by utilizing CAD programs. Kim's research group at KRISS developed stretchable, thin strain sensors and explored embroidery and laminating methods to make the sensors thinner and more flexible.

Despite the efforts delineated above, there is a lack of research concerning methods to standardize wearable robot systems and evaluate their performance and quality. Thus, in 2020, a collaborative research group from the mechanical engineering, apparel design, sports departments of UNIST, Seoul National University, Konkuk University, and the Korea Electronics Technology Institute, respectively, has been conducting research to develop muscle strength assistive clothing-like soft wearable robots for industrial workers. It will appear as a normal t-shirt and consist of pneumatic tubes and stretchable sensors. The group aimed to develop soft wearable robots, along with their standard performance, quality requirements, and evaluation methods.

The next step would be commercializing these developed smart clothing and wearable robots and make them to be successful in the market. These could be achieved by the product and process innovation (Jin & Cedrola, 2018, 2019); for example, integrating the design-driven development process, developing products considering brand concepts and positioning along with retail model, and pursuing continuous product and process innovation for their commercial success.

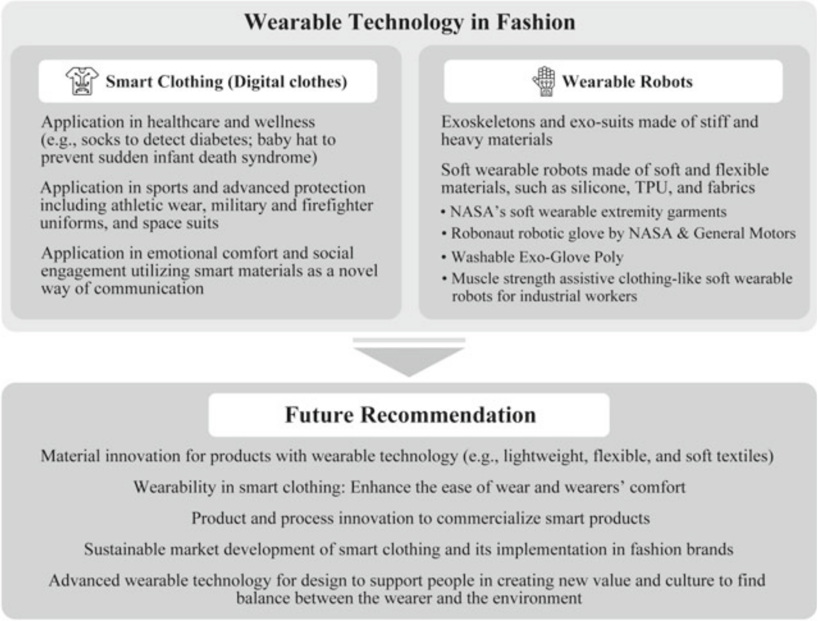
CONCLUSION AND FUTURE TRENDS

This chapter introduced wearable technologies, including smart clothing and wearable robots, and reviewed the relevant definitions, development history, and trends concerning such technologies. As one of the promising technologies to support the users' life, discussions regarding smart clothing and wearable robots have been approached from different perspectives. It became evident that the next generation of smart clothing and wearable robots would orient toward its social implications in the new digital ecosystem that has its physical and digital aspects connected to one another.

People would be reluctant to utilize and wear smart clothing and wearable robots if they are heavy and stiff, limit their movements, and are cumbersome to move around with. Thus, designers would need to consider the following aspects when designing future smart clothing and wearable robots: making wearable robots lightweight, flexible, soft, durable, thin, easy to wear and remove, easy to use and care for, stable in terms of their performance and construction, safe, more efficient in terms of battery use, and accurate and reactive in their performance. It would be even more preferable if wearable robots have the appearance of normal clothes that people can wear in daily life without garnering unwanted attention, as this can lead to the popularization of smart clothing and wearable robots. As smart clothing and wearable robots become more flexible, there will be more potential for sensors and actuators to function better, since they are presently not aligned with the areas of the body they are intended for, which could cause the wearable robots to operate only partially and limit the wearer's movements.

It is also crucial to develop an understanding of what kinds of smart clothing and wearable robots people prefer and are willing to wear. If directed efforts are undertaken, more people can wear such devices comfortably and utilize them frequently, which will ultimately enhance their quality of life and well-being. Related technologies could be applied to various areas, such as devices for pets, smart furniture and houses, airplanes, smart cars, sports and games, and education.

With the advent of smart clothing and wearable robots, the way we perceive, prioritize, and expand our lives will change dramatically. Hence, advanced wearable technology must be designed to support people in creating new value and culture to find further balance between the wearer and the environment. This may involve building a new communication platform to support the aging population or educating users to be more environmentally conscious while engaging with their innovative material, platform, and services. It has been a while that smart clothing and wearable robots were in the market, but there have been not many fashion brands that were succeeded with its implementation. It would be beneficial for fashion brands and developers in smart clothing and wearable robots to innovate the product and process in order to commercialize these smart products. Moreover, advanced materials, manufacturing technology and design standards, and new values and culture need to be ensured for smart clothing and wearable robots development to bridge the gap between the human and the environment through the circular economy for future wearables. Summary of wearable technology in fashion and future recommendation for its use are summarized in Fig. 3.1.



Wearable Technology in Fashion

Smart Clothing (Digital clothes)

Application in healthcare and wellness (e.g., socks to detect diabetes; baby hat to prevent sudden infant death syndrome)

Application in sports and advanced protection including athletic wear, military and firefighter uniforms, and space suits

Application in emotional comfort and social engagement utilizing smart materials as a novel way of communication

Wearable Robots

Exoskeletons and exo-suits made of stiff and heavy materials

Soft wearable robots made of soft and flexible materials, such as silicone, TPU, and fabrics

- NASA's soft wearable extremity garments
- Robonaut robotic glove by NASA & General Motors
- Washable Exo-Glove Poly
- Muscle strength assistive clothing-like soft wearable robots for industrial workers

Future Recommendation

Material innovation for products with wearable technology (e.g., lightweight, flexible, and soft textiles)

Wearability in smart clothing: Enhance the ease of wear and wearers' comfort

Product and process innovation to commercialize smart products

Sustainable market development of smart clothing and its implementation in fashion brands

Advanced wearable technology for design to support people in creating new value and culture to find balance between the wearer and the environment

Fig. 3.1 Summary of Wearable Technology in Fashion with Future Recommendation (*Source* Developed by the book editor)

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CHAPTER 4

3D Printing and Additive Manufacturing in Fashion

Lushan Sun

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

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INTRODUCTION

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

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

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

Direct Digital Manufacturing in Fashion

Advantages and Challenges in 3D Printing and Materials

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

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

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

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

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

Advantages and Challenges in 3D CAD

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

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

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

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

Innovations and Interdisciplinary Thinking in 3D Printed Fashion

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

Conclusion and Future Trends

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

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

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

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

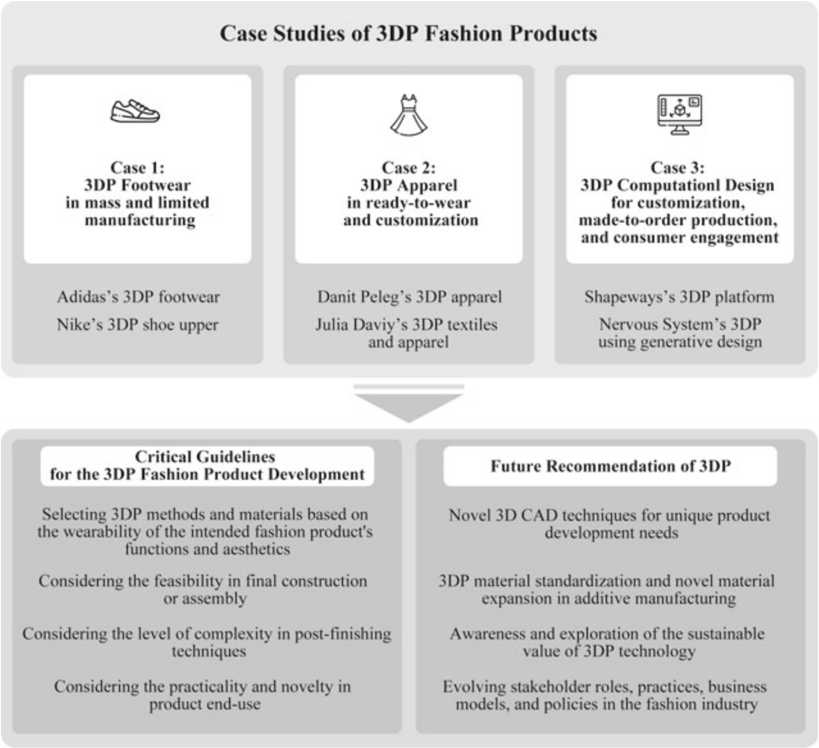

Fig. 4.1 Summary of Cases Studies of 3DP Fashion Products (*Source* Developed by the book editor)

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

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

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

Sources of Further Information

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

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

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CHAPTER 5

Automation with Robotics in Garment Manufacturing

Mir Salahuddin and Young-A Lee

Abstract The application of robotics in manufacturing industries has soared, facilitating automation of production lines. Despite the undeniable labor-intensive aspect of the apparel manufacturing industry, automation with robotics is the apparent future of this industry. This chapter covers the general role of garment automation in the fashion industry. The chapter introduces the fundamentals of robotics in fashion and the way it is implemented in garment manufacturing and illustrates automation practices occurring within garment production. The cases employing automated robotic systems are introduced by depicting the US-based factory's automation practices. The chapter also discusses the

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challenges in adopting automation and its potential to revolutionize the garment manufacturing industry.

Keywords Robotics · Automation · Garment manufacturing · On-demand manufacturing · Digital transformation

INTRODUCTION

The manufacturing industry is embracing smart manufacturing, also known as the Fourth Industrial Revolution (Industry 4.0), which entails the digital transformation of manufacturing in value creation processes to expedite the decision-making process, increase productivity, improve product quality, and save time and money. Industry 4.0 consists of numerous cutting-edge technologies (e.g., Internet of Things, smart sensors, augmented reality), and the application of robotics is one of them (IBM, 2021). Robotics technology is applied to enhance the speed and accuracy of the manufacturing process, which eventually leads to industry automation (IBIS World, 2018). Automation can generally be defined as the process of following a predetermined sequence of operations with minimal or no human labor, by the means of specialized equipment and devices that perform and control the manufacturing process (Nayak & Padhye, 2018). It reduces human intervention to a minimum, resulting in the conservation of labor and energy, as well as enhanced precision, accuracy, quality, and productivity. Automation is widely utilized in diverse sectors including manufacturing, healthcare, engineering, and supply chain.

Apparel manufacturing is a labor-intensive sector, where different processes are accomplished by highly skilled manual operations by employing traditional materials and equipment. Its production process consists of three stages: (a) pre-production (material preparation including line planning, sample development, sourcing, and scheduling); (b) production (several stages including fabric spreading, cutting, bundling, and sewing); and (c) post-production (where goods are inspected, finalized, and packaged) (Nayak & Padhye, 2018). Though the existing apparel manufacturing process is largely dependent on manual labor, it is transforming into an automated industry through the integration of robotics technology. To capture the overall benefit of integrating robotics application in the fashion industry, the current practices and challenges of robotic application, as well as its overall contribution to the fashion industry require discussions.

Fundamentals of Robotics

A robot is a computer-controlled machine that is programmed to move, manipulate objects, and accomplish work while interacting with its environment. According to the Robot Institute of America, a robot is defined as ‘a reprogrammable, multifunctional manipulator designed to move material, parts, tools, or specialized devices through various programmed motions for the performance of variety of tasks’ (Gupta & Arora, 2009, p. 309). Robotics can be categorized based on two distinct application areas: Service robots and industrial robots (WIRED, 2017). Service robots are being developed for a vast range of applications, including the regulation of unmanned aircraft for the military. Further, robot vacuum cleaners and rescue robots exemplify other applications. Robots in the industrial sector have been developed to meet industry needs. This industrial robot is defined as a programmable, mechanical device utilized in place of a person to perform dangerous or repetitive tasks with a high degree of accuracy (Wilson, 2014). In other words, industrial robots are completely autonomous machines, capable of performing specialized functional tasks, such as welding, painting, assembling, handling materials, or packaging in a warehouse or a manufacturing unit (Luce, 2019).

The application of robotics is increasing drastically within manufacturing industries, owing to its performance reliability and a wide range of benefits, such as curtailing operation costs, enhancing product quality and consistency, improving the employees’ work quality, enhancing production output rate, accelerating product manufacturing flexibility, reducing material waste, and improving workplace safety and health (Robotics Tomorrow, 2018). Especially, implementation of robotics in garment manufacturing has several advantages as follows: cost reduction, reshoring production, less negative environmental impact, and adding manufacturing flexibility.

Automation in Garment Manufacturing

The US, Europe, and Japan conducted extensive research and development on garment production automation processes in the early 1970s and throughout the 1980s (Jana, 2018). For instance, in 1984, through the combined effort of the Georgia Institute of Technology and the US Department of Commerce, a robotic system to sew the front pockets of a pair of trousers was developed (Tincher, 1984). Presently, the pre-production process (e.g., fabric spreading, cutting) can be accomplished by automatic machines (Vilumsone-Nemes, 2018). A fabric spreading automatic machine is utilized to place the fabric on the spreading table as per the entered data, such as fabric length, width, and ply counts. After fabric spreading, the next stage is to cut the multiple layers of fabrics following pattern pieces as per marker. This process is accomplished by an automatic cutting machine, where the cutting head automatically moves to cut the fabrics by following the marker. Automatic laser cutter, knife cutter, or water-jet system are utilized as cutting machines. These kinds of cutting machines can also detect the blade sharpness or identify a blunt blade by itself to prevent the operators from potential physical injuries, as well as to ensure the product quality. Benefits of using automatic cutting over manual cutting include higher efficiency and accuracy, ease of cutting single and multiple plies, and perfect cutting at first attempt (Nayak & Padhye, 2018).

In the garment production stage, material handling and the sewing process are the most crucial procedures. Material handling includes multiple steps, involving stiffening and bending, lifting, moving, mounting, and repositioning of the fabrics. These steps are accomplished by automated devices to assist with the sewing process. Sewing or joining fabric pieces together is mainly completed through a semi-automatic procedure, where a specific task is assigned to a designated machine. For instance, a sewing machine with an underbed thread trimmer cuts threads automatically once the stitching is completed. A sewing machine with an automatic bobbin changer automatically refills bobbins once all the threads have been consumed. A sewing machine with a special function can automatically stitch back pockets, belt loops, the waistband, and the bottom hemmer (Jana, 2018).

Currently, automation within garment production is limited to fabric spreading, cutting section or specific part of the fabric stitching, rather than creating complete garments utilizing industrial robots, such as sewing robots. According to the International Federation of Robotics (2020), the automotive (28%), electrical/electronics (23.5%), metal and machinery (11.7%), plastic and chemical products (5.0%), and food (2.9%) are the top industries where industrial robots are mostly installed in 2019.

In 2016, a total of 250 units of industrial robots were sold to the textiles, apparel, and footwear sectors, which accounts for only 0.085% of the total industrial robots. China was the market leader, utilizing 133 units industrial robots in textiles, apparel, and footwear, followed by Italy (59 units), the US (39 units), Germany (10 units), and Japan (9 units). In comparison to 2010, the implementation of robotics within the fashion industry increased by 58% in 2016 (International Federation of Robotics, 2017; Kucera & Barcia de Mattos, 2019).

Cases of Automation Practices in Garment Production

Case 1: Sewbot by SoftWear Automation

In 2012, 'Sewbot' was developed at Georgia Tech's Advanced Technology Development Center and later, an Atlanta-based startup company, SoftWear Automation, was established for Sewbot's commercialization (Ruvo, 2018). It can perform automated sewing operations for home goods, footwear, and apparel products. SoftWear's mission of launching Sewbot was to allow the manufacturers sewing locally to reduce their supply chain lead time and produce higher quality products at a lower cost (SoftWear Automation, 2020a). Palaniswamy Rajan, the chairman and CEO of SoftWear Automation, also stated that Sewbot could bring the supply chain closer to the consumers and reduce the energy loss; thus, manufacturers can curb carbon footprints and contribute to the improvement of the environment (SgT Group, 2017).

Sewbot was developed based on a modular design approach to produce different types of sewn products by utilizing a highly calibrated machine-vision system to detect fabric distortions and track an exact needle placement within half a millimeter of accuracy (Device Plus, 2018; Robotics Tomorrow, 2019). This robot has four axes, meaning, it can move at a 360° angle, enabling it to pick the fabric and place it for sewing operations directly (Venkatesh, 2018). Sewbot is currently capable of manufacturing numerous items, including pillows, mats/rugs, automotive mats, towels, mattresses, and t-shirts. For example, this robot can produce up to 480 pillows, 960 mats, 800 automotive mats, 480 microfiber towels, 395 mattress covers, and 1,142 t-shirts per 8-hour shift. For t-shirts especially, it only takes 22 seconds to assemble one. This autonomous machine could produce a t-shirt twice as fast as a manual sewing machine. In other words, one operator of the Sewbot machine can produce the same number of t-shirts as 17 operators can by the means of manual sewing machines in the same timespan (Guizzo, 2018; SoftWear Automation, 2020b).

In 2017, the Chinese clothing manufacturer, Tianyuan Garments Company, installed 21 Sewbot lines to produce t-shirts with an investment of 20 million US dollars in the Little Rock's Arkansas factory. The Little Rock plant's goal was to produce around 24 million t-shirts a year by 2021 and one billion t-shirts within the next 10 years. According to Tang Xinhong, the chairman of Tianyuan Garments, the approximate cost of each t-shirt is 33 cents, and he believes that even the cheapest labor market in the world cannot compete with them because of the application of robotic systems in their manufacturing unit (Borneman, 2017; Guizzo, 2018; Twyg, 2020). According to Tianyuan Garments Company, with their implementation of robotic systems in the garment production line, automation does not adversely impact the human workforce, since 3 to 5 workers are required for each production line to support the robotic system (SgT Group, 2017).

Prior to SoftWear Automation, there were several attempts to introduce robotics in garment manufacturing, but these were not commercially successful because of their inability to handle soft materials like fabrics (Guizzo, 2018). Earlier sewing robots were designed to handle rigid objects which treated fabrics with starch to make them as stiff as steel sheets. In contrast, Sewbot can handle fabrics without utilizing starch. However, it is still challenging to handle fabrics because of their different weights and various fiber contents and textures. Since fabrics are prone to be stretched or deformed and their behavior is difficult to regulate, SoftWear Automation developed a specialized camera that could capture more than 1,000 frames per second together with the image-processing algorithm, which can detect each thread of the fabric (Georgia Research Alliance, 2021). Moreover, SoftWear Automation built a robotic manipulator to imitate the process of handling fabrics by the means of a conventional sewing machine operator. It can guide a piece of fabric through a sewing machine with high precision and allow it to make automatic corrections of material distortions (Guizzo, 2018). SoftWear Automation implemented two systems to move the fabric panel around: (a) the four-axes robotic arm with vacuum gripper capable of picking and placing the fabric on the sewing table and (b) the 360° conveyor system that utilizes a spherical roller attached with the sewing table to slide and rotate fabric panels at a high speed (Guizzo, 2018). Sewbot is the consolidation of advanced robotics technology to perform sewing operations, which requires skilled workforces to operate and run the machine.

However, within the existing mechanism, Sewbot can produce mostly flat, square, or round-shaped products, such as rugs, pillowcases, towels, and less complicated garments, such as t-shirts. Their next focus is to produce jeans, dress shirts, and uniforms, which are more complicated than t-shirts. Although they are concentrating on upgrading their sewing robots, the most complicated products, such as a bridal dress, still require traditional human expertise (Guizzo, 2018).

Case 2: The Sewbo Robot

In 2016, Sewbo Inc., a Seattle-based company founded by Jonathan Zornow in Washington, introduced an industrial robot called 'Sewbo', which is capable of handling flexible fabrics and thus, assisted to sew t-shirts in collaboration with traditional sewing machines. Sewing machines are operated by a robot operating system to accomplish synchronized operations with the Sewbo robot. This robot stiffens the fabrics, which can easily be molded or welded like a sheet metal before constructing the garment. Water-soluble materials, such as polyvinyl alcohol, are used to stiffen the fabrics. At the end of the manufacturing process, the stiffener is removed by washing the fabric with hot water, which softens the garment. The company claimed that their technology would create higher quality products with a lower cost and reduce the supply chain lead time (Sewbo, 2016). Bluewater Defense Inc., a leading uniform manufacturer for the US Department of Defense, has been utilizing Sewbo in a pilot project to produce military uniforms (Advanced Robotics for Manufacturing, 2019).

The Sewbo robot can be utilized repeatedly to grip fabrics and place them on sewing machines for a specific size and operation. However, it requires reprogramming when garment sizes, designs, or operations are altered. It further requires multiple Sewbo robots to conclude the full operation of a specific garment style (Nayak & Padhye, 2018). In addition, the fabrics which are waterproof or susceptible to damage after soaking cannot be worked on by Sewbo. The use of Sewbo may increase the garment price, owing to the recurrent use and removal of chemicals utilized to stiffen fabrics (Kucera & Barcia de Mattos, 2019).

Case 3: Grabit's Robotic Arms

Grabit Inc., a robotic manufacturing company based in Sunnyvale, California, invented robotic handles operated by static electricity, which can lift different kinds of objects, including soft fabrics, eggs, and boxes up to 50 lbs (Grabit, 2021). Robotic arms have been applied in car manufacturing facilities for years to assemble different car components, but this concept has not been effectively implemented in garment manufacturing because of the fabrics' flexible nature, which is difficult to maintain along with the desired shape. To overcome this limitation, Grabit has been utilizing electro adhesion, the type of static electricity that can hold and maintain the shape of soft fabrics (Brustein, 2017).

Grabit's robotic handles can arrange different pieces of shoes 20 times faster than a human. Large retailers (e.g., Ralph Lauren, Tommy Hilfiger) invested in this robotic arm to accelerate the manufacturing of garment parts, such as collars and cuffs of button-up shirts. Nike installed around 12 robotic arms in its shoe manufacturing factories in China and Mexico (Kucera & Barcia de Mattos, 2019). By utilizing Grabit's material handling robot system, Nike can manufacture around 600 pairs of shoes within an eight-hour shift (Robotics Tomorrow, 2021).

Case 4: Adidas' Speed Factory

Adidas, a sportswear brand established in 1949 in Germany by Adi Dassler with the mission to provide athletes the best possible sports equipment, currently owns over 2,500 retail stores and has employed 62,000 people all over the world (Adidas, 2021). Adidas mainly outsourced its goods, including shoes, clothing, and accessories to contract factories in Asia. The production process takes considerable time before the product reaches the customer after placing the order. Therefore, in 2015, Adidas launched an automated shoe manufacturing plant, called 'Speed Factory' in Ansbach, Germany with the goal of delivering goods expeditiously to customers in their major markets in the US and Europe. The company designed Speed Factory to produce customized products three times faster than traditional factories (Green, 2018) and was expected to produce 500,000 pairs of shoes annually from this plant, whose operations are completely automated and facilitated by robotics and 3D printing (Gries & Lutz, 2018).

Two years later, Speed Factory was opened in Atlanta, Georgia with the goal of reducing the stock and the transportation time through localized production (Green, 2018). Multiple steps are involved in shoe-making. Even with the robots, on an average 60–80 steps require completion to produce a pair of shoes, which restricted Adidas to producing only certain kinds of running shoes by utilizing the complete automation process. Thus, in 2019, Adidas declared the closing of both the factories, in Germany and the US, by April 2020 and relocated their manufacturing plants in Asia. (Hernandez, 2020; Van den Broeke & Paparoidamis, 2021). In sum, Adidas' Speed Factory started to facilitate the localized production to reduce the manufacturing and transportation lead time; however, it failed to continue because of limitations associated with the automation process to produce a diverse range of product categories for mass consumers.

Case 5: Levi Strauss & Co's Automated Laser Technology

Levi Strauss & Co., an American apparel company known for the Levi's brand of jeans, initiated a future-led execution (F.L.X.) project, which is a new operating model converting denim finishing from the manual hand process to the automated system by applying computer-controlled automated laser technology (Levi Strauss, 2018). In general, various effects are generated by subjecting denim jeans through the dry and wet finishing processes. Dry finishing involves creating abrasion and whiskering effects in pockets, belt loops, knees, or the rear portion of jeans through manual labor. This process is accomplished by hand sanding with a grinding wheel or applying resin to the targeted areas. Wet finishing comprises chemical processes by removing denim colors with stone washing or through the utilization of potassium per manganate. Both finishing processes are time consuming and unsustainable considering the workers' health and its environmental impact (Cotton Works, 2021).

The F.L.X. project introduced laser technology that creates finishing effects on jeans through laser operation. It reduced the finishing time drastically from an hour to 90s per garment. This transformation reduced the manufacturing lead time from over six months to a week or a day, which is highly advantageous since unfinished garments that require finishing are always available. This helps fulfill the inexhaustible on-demand finish orders nearer to the market. It also promoted sustainable apparel manufacturing by reducing the applications of chemicals in the finishing process (Levi Strauss, 2018); approximately 25% of Levi's global bottom products were produced with automated laser technology as part of the F.L.X. project (Sourcing Journal, 2019).

The company invested in training its employees on software development and laser operations to maximize the value of this new operating model (Levi Strauss, 2018). The F.L.X. project eventually promoted on-demand localized production; however, this was only limited to the jeans finishing and not applicable to the entire manufacturing process. Despite some limitations, Levi's F.L.X project reduced production lead time, brought sustainability within the manufacturing process, promoted on-demand production, and enhanced workers' skills in operating advanced technology and software development.

Summary of the Automation Cases

According to the case of Sewbot by SoftWear Automation, the application of robotics in garment manufacturing supported the localized production and reduced the supply chain lead time. The application of robotics enhanced the efficiency of the production process along with the generation of higher quality products at a lower cost. Automation increased the demand for the skilled workforce required to operate these machines. This case study also demonstrated the limitation of the existing sewing robotic machines, which cannot be utilized for developing products belonging to diverse categories.

The case of Sewbo exhibited the garment automation procedure through the handling of flexible fabrics. However, the inability to handle diverse fabric types and the associated extravagant costs are the limitations of this process. Through the case of Grabit's robotic arms, it is evident that automation of the material handling procedure increases productivity and efficiency of garment production. The case of Levi Strauss & Co. supports localized production by applying automated laser technology in the jeans finishing process. The case of Adidas' Speed Factory reveals that utilizing robotics in mass production is not yet financially viable, provided that is not applicable for producing diverse products. Figure 5.1 showcases the summary of garment automation cases presented in this chapter along with its challenges that are discussed in the following section.

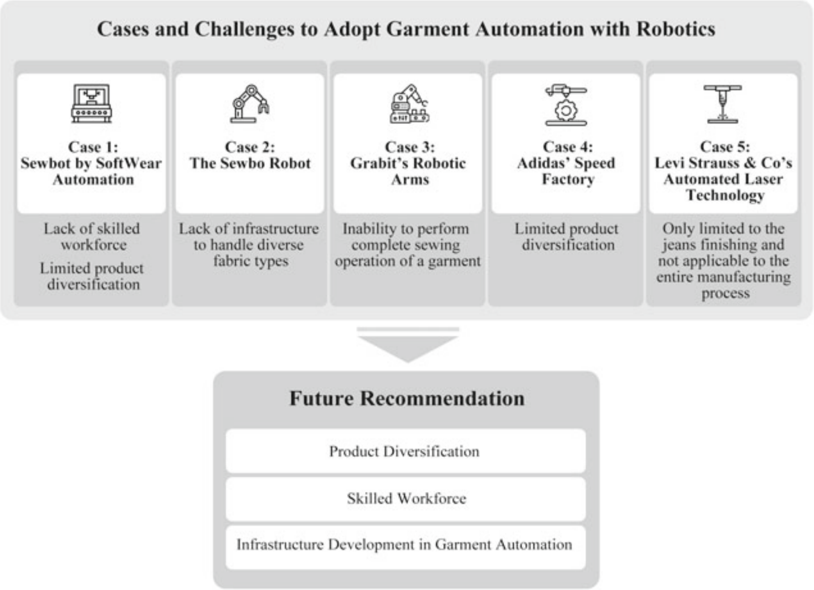

Fig. 5.1 Summary of Garment Automation Cases and Challenges (*Source* Developed by the authors)

CHALLENGES OF ADOPTING GARMENT AUTOMATION

The application of robotics technology within garment manufacturing brings automation to the production line, reduces production lead time, saves money, and eventually contributes to sustainability. Despite such benefits, automation in garment manufacturing is still in its early stages compared to other industries. For thorough implementation and economic viability, challenges of adopting garment automation should be addressed, which include (a) sewing robots possessing limited ability in the production of diverse apparel products; (b) gaps in skilled manpower to operate sewing robots; and (c) lack of infrastructures for complete implementation of robotics in garment manufacturing (see Fig. 5.1).

Limited Product Diversification

The current sewing robots are only capable of producing basic apparel categories (e.g., t-shirts), which prevent garment manufacturing units from adopting robotics technology to produce apparel with complicated design requirements (e.g., dress, jacket, coat). The automotive industry is the leading manufacturing industry in automation with robotics application, which brings a variety of product mixes within their manufacturing system that enables them to produce massive quantities of products for different kinds of consumers (Thomas & Kandaswamy, 2015). For instance, the car manufacturing company Toyota annually produces 10 million vehicles in their automated manufacturing plant with diverse product mixes (e.g., compact cars, pickups, SUVs, trucks, sports cars) (McFarlane, 2019).

It is evident that the mechanism of the existing sewing robots requires modification or improvement based on the product category so that the same kind or different kinds of sewing robots can produce diverse products (basic and complex garments) without any hindrance. The sewing process in the fashion industry is substantially complicated compared to other industries, since garments, the closest environment to the human body, require various considerations of human factors before production to ensure their suitability for wearers. Apparel designers consider a number of human factors (e.g., comfort, mobility, size, shape, safety, protection) while designing apparel (LaBat, 2006). Existing sewing robots must consider those factors while manufacturing complicated apparel (e.g., dress, jacket, coat). To maximize the advantages of garment automation, it is imperative to overcome the existing limitations of sewing robots so that they can sew a vast range of product categories beyond the basics, which may motivate garment manufacturers to incorporate robots into their production units.

Gaps in Skilled Workforces

There is an enduring concern regarding the effects of industrial automation on human labor; however, a study demonstrates that the overall impact of automation on unemployment is negligible (Parschau & Hauge, 2020). Moreover, the employment data in manufacturing during the period of 2010–2017 demonstrates a positive relationship between the percentage of employment in manufacturing and the percentage of robot installations (International Federation of Robotics, 2018; U.S. Bureau of Labor Statistics, 2021). In the US, both, manufacturing jobs and robot installments, have been increased during this time. According to the World Economic Forum (2018), approximately 133 million new roles may emerge worldwide by 2022 demanding a new set of skills pertaining to robotics and automation, owing to the increased requirement of incorporation of robotics within the manufacturing units. New skillsets or talents are highly required within the workforce to overcome the challenge that automation poses (McKinsey, 2018). Jeff Bernstein, the president of the Association for Advancing Automation stated:

> Currently we are in a phase of growth and development for automation. As lower-level tasks are automated with advanced technologies such as robots, new job titles and industries arise across nearly every economic sector and new skills are required. The bad news is employers can't fill jobs fast enough. Manufacturers estimate there may be as many 2 million jobs going unfilled in the manufacturing industry alone in the next decade due to a skills gap. (Borneman, 2017)

To incorporate automation with robotics in garment manufacturing, one of the main challenges is recruiting skilled manpower that can work with, service, and operate robots and automated systems, having acquired the fundamental knowledge on apparel quality and production systems (Gerber Technology, 2019). Futuristic insights and strategic planning are essential from both the industry and the academia to train the future workforce in garment manufacturing and update the course curriculum in textiles and clothing-related programs, comprehensively reflecting the skills required for the emerging needs of the automated garment industry.

Lack of Infrastructures in Garment Automation

According to Spencer Fung, a group CEO of Li and Fung, a supply chain management company, believes that digital supply chain no longer relies only on-cost optimization, but rather, depends on expediting processes by reducing the lead time for the products to be available in the market on time to satisfy the growing consumer demand. Within the digital supply chain, speed can be achieved through on-demand product development, on-demand manufacturing, and ensuring digital distribution at the retailing stage (Crawford, 2019; Jin et al., 2019).

Nowadays, there is a significant progress in digital retail distribution, where consumers can receive their products through online shopping, compared with the other stages of the product development pipeline. The main components of on-demand product development and on-demand manufacturing are (a) planning, designing, and development and (b) garment automation, also known as digital manufacturing, respectively (Crawford, 2019; Gerber Software, 2020). To attain comprehensive incorporation of the digital supply chain in the fashion industry, the complete integration of the software and manufacturing system from the initiation of product planning to production is crucial (Gerber Software, 2020). It is evident that planning, designing, and product development stages are continually updated in accordance with the emerging technologies, but the efficient and effective way to completely integrate the digital manufacturing process into the fashion industry is still limited, which prevents the absolute adoption of the digital apparel supply chain.

Conclusion and Future Trends

The imminent adoption of automation encourages on-demand or made-to-order manufacturing, which enables fashion brands to order as little as one piece at a time and produce only what is likely to be sold to avoid overproduction and make apparel less likely to be discarded after its use (Vogue Business, 2020). Micro-factory, a localized production unit, is designed to manufacture a small batch of production based on the consumer demand, where a flexible robotic system is a key adopted technology, which aids in running micro-factory.

A single automated micro-factory should be capable of handling the operations involved in each stage of the digital supply chain, including order processing, design, modeling, coloration, labeling, fabric cutting, robotic handling, sewing, finishing, and shipping (McKeegan, 2018). Contrary to mass production, micro-factory does not require a complex supply chain with extended lead time. Further, on-demand manufacturing prevents the possibility of unsold inventories (Montes & Olleros, 2020). The primary difference between micro-factory and the traditional factory resides in their business model, where the former focuses on consumer demands rather than a production-led approach. This enables the fulfillment of consumer demands without the utilization of massive production and warehouse facilities, which eventually conserves energy and ensures sustainability (McKeegan, 2018).

The advanced technology, including sewing robots, can help entrepreneurs initiate on-demand, customized ordering through micro-factory. For instance, the apparel firm Nimbly utilizes the 3D whole garment knitting process to develop custom-knitted garments, which are directly shipped to the customers within 48 hours (Nimbly, 2021). OnPoint Manufacturing (OPM), an on-demand apparel firm, incorporated an integrated software system for the purpose of product design, manufacturing, and delivery to provide consumers with customized garments within a shorter time span (OnPoint Manufacturing, 2019) but unfortunately, the company closed their business in 2021. In 2017, the online retail company Amazon received a patent on their on-demand manufacturing system for customized apparel production, where an integrated computerized system (e.g., textile printer, fabric cutter, manufacturing line, camera system) is implemented to fulfill the consumer orders (Rey, 2017). This emerging approach presents a new opportunity for small business entrepreneurs or independent designers to attain success in the disruptive fashion industry.

With the advent of Industry 4.0, the labor-intensive fashion industry has been transforming to embrace the implementation of robotics in garment manufacturing to fulfill the present requirements and future demands. The application of robotics in the fashion industry enhances the accuracy and efficiency of garment production, which ultimately contributes to reduced lead time in the fashion supply chain. Currently, fashion brands also embrace other cutting-edge technologies (e.g., RFID, AI) throughout their retail distribution channel to enhance the operational and customer service efficiency. However, the success of the entire fashion supply chain relies on how quickly apparel manufacturers can embrace automation in garment manufacturing and adapt to this advanced technology in their production unit. With the disruptive digital movement in the fashion industry, it is crucial to overcome the existing challenges by (a) improving the capability of current sewing robots to produce products belonging to diverse categories, beyond the basic clothing items; (b) embracing skilled workforces in garment automation; and (c) building a seamless infrastructure to implement automation with robotics into the garment production line. In the long run, automation in garment manufacturing can facilitate on-demand localized production, which promotes sustainability practices in the industry.

SOURCES OF FURTHER INFORMATION

For additional information and news regarding technology innovation in garment automation with robotics, please reference the following collection of resources.

- Grabit Inc. (https://grabitinc.com/): A robotic manufacturing company invented robotic handles operated by static electricity, which can lift different kinds of objects, including soft fabrics up to 50 lbs.
- Levi Strauss & Co's Project F.L.X. (future-led execution) (https://www.levistrauss.com/2018/02/27/project-f-l-x-redefines-future-jeans-designed-made-sold/): A company's new operating model that ushers denim finishing into the digital era, by replacing manual techniques and automating the jeans finishing process.
- Nimbly (https://www.nimblymade.com/): An on-demand manufacturing company using 3D knitting machine, partnered with digitally native brands and taking orders from their websites in real-time. They knit and ship products directly to the end customer, within 48 hours.
- Sewbo Inc. (https://www.sewbo.com/): A world's first company introducing an industrial robot to sew a T-shirt, achieving the long-sought goal of automation for garment production.
- SoftWear Automation (https://softwearautomation.com/): An Atlanta-based advanced machine-vision and robotics startup by using automated Sewbots which enable on-demand manufacturing.

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CHAPTER 6

Artificial Intelligence in Fashion Manufacturing: From Factory Operation to Advisory Role

Kassandra Ross

Abstract The fashion industry has experienced an unprecedented application of artificial intelligence (AI) in the last decade. At the manufacturing, distribution, and consumer retention stages, the implementation of AI technologies has afforded fashion retailers assistance in diverse fields, such as production, trend analysis and forecasting, hyperpersonalized marketing, and overall consumer engagement. Specific technologies, such as robotics, intelligent sensors, digital agents, and smart algorithms and machine learning, have altered the trajectory of the fashion industry. By delineating integral cases of technologies in fashion manufacturing and operation, this chapter aims to enhance the reader's understanding of where the fashion industry stands in relation to AI and provide discussion

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points where these advances are progressing in terms of productivity and sustainable efforts for the industry, both economically and theoretically.

Keywords Artificial Intelligence · Fashion industry · Manufacturing and operation · Internet of Things · Robotics

INTRODUCTION

The last decade has ushered in an unprecedented application of artificial intelligence (AI) technologies in the fashion industry, which accounts for 1.5 trillion US dollars of the global market (O'Connell, 2020). The fashion industry is a strenuous market for manufacturers to navigate. With volatile consumer trends, fluctuating labor costs, high product variation, and short product lifecycles, manufacturers are constantly challenged. Although no single definition of AI has been offered by the extant literature, scholars agree that AI generally refers to a data acquisition system, with some degree of technological autonomy, that is designed to accomplish specific goals intelligently (Marr, 2018). The implementation of AI in the fashion industry has afforded manufacturers smarter tools in managing the evolving global market. Such applications prevail over classical techniques in regulating market complexities (Guo et al., 2011). In the present market scenario, fashion manufacturers are constantly seeking ways to enhance productivity, not only to survive but to thrive (Bonfanti et al., 2018).

Most AI applications in fashion manufacturing can be observed as having been implemented over the last decade. According to a systematic literature review of 149 research studies on AI integration in the fashion industry, 56% of the total number of publications between 1989 and 2018 have been published since the year 2009, suggesting that although AI methods have been utilized for roughly 30 years, their earnest adoption has taken place within the last decade (Giri et al., 2019). Such AI technologies at the manufacturing level include anything from the integration of Internet of Things (IoT) and smart warehouses (Liu et al., 2018), to optimizing the dispatch of fashion assortments (Wang et al., 2018), and creating forecasting tools to revamp fashion production (Sajja et al., 2021).

By outlining the integral cases of AI in fashion manufacturing, this chapter aims to enhance the reader's understanding of how AI advancements have been utilized to enhance productivity and promote sustainable efforts in the fashion industry. Directed efforts toward the integration of AI into fashion manufacturing are challenged by the lack of development and improvements essential for the process. Indeed, the integration of AI in the fashion industry has been sluggish in comparison to several other consumer industries, such as the automated car industry, which adopted AI considerably early (Schwab, 2016). Further, the majority of modern AI advancements in fashion manufacturing remain largely academic and theoretical, where practical applications have been slow to fruition in the actual factory setting (Giri et al., 2019). Given the volatile character of the fashion market, the industry could significantly benefit from the rigorous implementation of AI in manufacturing. Nonetheless, this chapter summarizes both academic/theoretical and industrial advancements and applications of AI in fashion manufacturing, in the factory operation setting, and as a smart advisory role.

AI in Fashion Manufacturing and Factory Operation

Each stage of the fashion manufacturing process is complex, comprising three consecutive phases: pre-production, production, and post-production (Abd Jelil, 2018). The pre-production phase of manufacturing includes early processes, such as material sourcing, cost analysis, and product approval. The production phase involves the process of cutting and sewing garments, and the post-production phase entails product pressing, packaging, and dispatching (Abd Jelil, 2018; Kumar, 2005; Scholz-Reiter et al., 2009). The process of producing garments and distributing them to consumers is typically executed through an extensively detailed, sequential procedure (Scholz-Reiter et al., 2009). Since the process is linear (i.e., all steps must be undertaken in a consecutive manner), under the strains of erratic market fluctuations, manufacturers must make complex and often cursory decisions. The introduction of recent AI methodologies has certainly assisted, or poses the potential to assist, addressing such decisions.

Further, manufacturers require a substantial depth of knowledge regarding the fluctuation of fashion trends, forcing them to demonstrate flexibility in making manufacturing decisions. Indeed, numerous scholars argue that the fashion trend-cycle has been disrupted in recent years by consumers' adoption of real-time technologies, such as social media (Bendoni et al., 2015). Fashion ideas, trends, and information are transmitted and adopted at unprecedented speeds, disrupting the traditional diffusion process of fashion innovations. In the era of social media, real-time data can be accumulated by fashion managers to make more accurate and speedy decisions that impact the manufacturing cycle. The following section of the chapter provides pertinent applications of AI in the physical manufacturing setting concerning product inventory and planning.

The Physical Factory Setting and Product Inventory

In the case of large-scale fashion manufacturing, production occurs within the factory setting. Although the adoption of automation in garment manufacturing has gained traction, the use of manual labor still takes precedence in 80% of all activities performed in the factory complex (Scholz-Reiter et al., 2009). In a traditional factory or a warehouse, supply chain operations such as garment creation, product inventory, and product dispatch, are executed by humans. However, scholars argue that due to the advancements in AI technologies, the use of human resources poses time-consuming, wasteful, and unsustainable end results (Liu et al., 2018). The intricacies of the garment supply chain further complicate manual processes, where errors often occur in processes on the product line development and during inventory counts (Scholz-Reiter et al., 2009). Thus, transforming traditional factory settings to 'smart' spaces is imperative.

Perhaps the most remarkable and comprehensive application of AI in the factory setting is the smart warehouse. According to Liu et al. (2018), smart warehouses are unmanned, paperless, and automated warehouses that conduct all factory operations, from product pickup to bookkeeping. The transformation from a traditional warehouse to a smart warehouse relies on the use of a Cyber-Physical System (CPS) (Liu et al., 2018). A CPS is able to generate a virtual copy of the physical manufacturing processes in a warehouse and enable objects within a production facility with 'smart' capabilities through Wi-Fi access points, Bluetooth beacons, radio frequency identification (RFID) tags, and robotics (Liu et al., 2018). The fashion brand ASOS has recently implemented smart warehouses in their manufacturing (Hollis & Rice, 2020). The benefits of smart warehouse automation, such as shipping logistics, have enabled ASOS to be a worldwide fashion brand competitor (Hollis & Rice, 2020).

To tackle and resolve problems related to product descriptions and inventory counts, a number of warehouse settings, whether they have transitioned to the highest degree of a smart warehouse or not, have implemented RFID technology to automate the identification of product inventory. RFID technology is relatively affordable for manufacturers (Liu et al., 2018), where products like garments are equipped with smart sensors or microchips that are tagged with identifiable information, such as garment color, size, and geographical location. The data from RFID tags are paired for transmission to reading devices, such as 'smart' shelves in a warehouse, enabling product tracking for warehouse and distribution managers. Utilizing AI to track the movement of inventory on shelves and throughout a manufacturing facility allows for a better flow of inventory data and knowledge over the manufacturing supply chain, from production to product container dispatch (Scholz-Reiter et al., 2009). RFID technology has been in development for several decades, with commonplace implementation in commercial manufacturing beginning in the 1990s (Chawla & Ha, 2007). Indeed, RFID is readily implemented within the fashion industry. For instance, the 100 billion US dollar apparel company, Nike, recently purchased an AI startup company called Celect to implement RFID technology for inventory optimization with data analytics to stock physical stores with the most effective products per location (Rejcek, 2019).

In 2012, the mega-retailer Amazon built a 775 million dollar Kiva system, where robots were utilized to carry and arrange products in warehouses. The implementation of robotics in manufacturing, where other items are enabled with AI through a CPS, allows manufacturers to operate a smart warehouse at its full capacity; robots are able to work among the backdrop of IoT-driven processes (Yerpude & Singhal, 2018). Robots that are functioning in conjunction with other IoT sensors in a factory have the potential to best manage production processes, where generated data enables an entire system to interact with itself to build a personal, self-contained history of interaction and inventory (Yerpude & Singhal, 2018). However, achieving optimal collaboration between robots and IoT-enabled sensors in a factory poses some challenges. Researchers are currently assessing potential solutions to facilitate cooperative methods between various technologies in IoT-enabled factories. These methods will assist the transformation of a single warehouse to be highly dimensional, like through the implementation of machine learning and reinforcement algorithms enabled in smart devices (Liu et al., 2018).

In addition to implementing a complete IoT landscape, such as in the case of a smart warehouse, a number of manufacturers have simply sought the assistance of AI technologies in designing physical factory space and assembly line optimization. When it comes to the production of a garment assembly line, assigning workstations with specified tasks and timeframes to enable the sequential movement of products from one station to another is essential for productivity. This is known as the assembly line balancing problem, where manufacturers assign workstations with exactly the right amount of work within a specific timeframe, minimizing the idle time between and among workstations (Abd Jelil, 2018; Ünal et al., 2009). AI has been used to implement soft computing methods, such as assembly line balancing algorithms, to address and simulate line optimization in certain factories (Abd Jelil, 2018; Ünal et al., 2009).

Several studies in the fashion industry have historically developed algorithms for assembly line efficiency, using simulations to test the effectiveness of such proposals (Chen & Harlock, 1999; Lee et al., 2000). In one study, Ünal et al. (2009) computed a heuristic algorithm to detect bottlenecking workstations that limit the productivity in a garment assembly line. Researchers experimented with various line configurations and simulated scenarios to test the effectiveness of the algorithm. Findings revealed that workstations physically set up in a U-shape were more productive and advantageous than those in a straight line (Ünal et al., 2009). Using AI as an evaluation tool in creating and simulating assembly line algorithms generates data for the purpose of experimentation, after which the most effective methods may be implemented by fashion manufacturers to accomplish maximum productivity among actual workstations.

Similarly, soft computed algorithms have been implemented in optimizing the relative positions of machinery in a factory setting. Facility layouts are often augmented for manufacturing product varieties. Indeed, since garment manufacturers are often producing several kinds of pieces with different designs in one factory, the layout of machinery becomes important to enhance the workflow, which varies among products. Altering layout designs is expensive for manufacturers, and poor design can result in inefficiency and inflexibility in operations (Abd Jelil, 2018).

Thus, implementing AI in modeling machinery on the floor is an important parameter in the factory setting in order to achieve overall production efficiency. In one study conducted by Ulutas and Islier (2015), machine layouts in footwear facilities were examined with several simulated scenarios using real data and a clonal selection-based algorithm. Researchers suggested that in footwear manufacturing, like many other apparel manufacturers, machine layout and re-layout decisions must be made to consider vast product varieties in small quantities among several workstations (e.g., leather cutting, steam ironing, and hammering) to suit a single design creation.

One example of an industry partner who models and designs warehouse configurations for fashion manufacturers is the smart solutions company, Interlake Mecalux. This company was hired by the sportswear retailer, Adidas, to design a major product fulfillment center based on computing solutions to optimize the product flow process. Interlake Mecalux's solutions have enabled Adidas to prepare orders in just two hours (Interlake Mecalux, n.d.). Through AI-simulated scenarios and suggested algorithms, manufacturers can optimize workstation layouts, revamping production, and preventing unnecessary costs. Table 6.1 presents a summary of AI technologies in the physical factory setting and product inventory phases of fashion manufacturing that are presented in the following section.

AI in Product Planning and Quality Assurance

When it comes to the large-scale production of fashion items, the planning and scheduling of products are critical in ensuring an optimal flow of information and resources between manufacturers and consumers (Abd Jelil, 2018). The implementation of AI in these areas has largely been attributed to soft computing algorithms and computer simulations designed for effective product planning and scheduling. The processes involved in this step of manufacturing include cut-order planning (the cutting of fabric for apparel orders), marker making (the process of cutting pieces of fabric into a pattern), and fabric spreading (the process of laying fabrics on top of one another to predetermine a cut-order plan) (Abd Jelil, 2018). Traditionally, the planning and scheduling of garment manufacturing depends on the experience of managers, which can be assessed by their personal histories and performances in handling other

Table. 6.1 Summary of AI technology use cases in fashion manufacturing

Fashion Manufacturing Category	*AI Technology*	*Description*	*Implementation by Fashion Brand/Entity:* Technology Name *(Year)*
Physical Factory Setting and Product Inventory	Smart Warehouse	An automated warehouse that conducts all manufacturing operations enabled through an assortment of ‘smart’ software and devices	ASOS: *Smart warehouse technology* (2020)
	Radio Frequency Identification (RFID)	An electromagnetic identification system used to identify and track tags associated with product inventory	Nike: *Celect RFID system* (2019)
	Robotics	The use of robotics to move and/or manufacture inventory in a warehouse	Amazon: *Kiva system* (2012)
	Computed Algorithms	Algorithms designed to simulate product assembly line balancing, efficiency, and machinery positioning in a manufacturing warehouse	Interlake Mecalux: *Adidas’ fulfillment center design* (2021)
Fashion Product Planning and Quality Assurance	Computed Product Planning and Dispatch Simulations	Simulations through digital software and/or devices for product planning, scheduling measures, assortment packing, dispatching, and shipping	Amazon: *Patented on-demand clothing manufacturing system* (2017)
	Sewing Automation	The use of robotic automation in textile sewing manufacturing	Jonathan Zorno: *Sewbo* (2016) SoftWear Automation: *LOWRY* (2018)

Fashion Manufacturing Category	*AI Technology*	*Description*	*Implementation by Fashion Brand/Entity:* Technology Name *(Year)*
	Systematic Product Quality Control and Assurance	Systematic product inspections conducted through automated processes, such as identifying sewing defects and product color matching	Dongguan Yunji Zhihui: *Garment visual inspection and measurement machine* (2021)
Fashion Aesthetics and Hyperpersonalitzation	Garment Sensory Modeling and Apparel Designing	Computational modeling of predicting textile sensorial comfort	Zolando: *AI-powered fashion design for consumers* (2020)
	3D Rendering/CAD Garment Preference Modeling	The use of digital software in modeling fashion products, consumers' fashion aesthetic preferences, and/or printing fashion products	Facebook AI: Fashion++ (2019) Nike: *Nike Fit foot scanning AI* (2019)
Fashion Forecasting and Competitor Analysis	Computed Trend Analysis Modeling	Computational models designed to highlight patterns in time-series, cross-sectional, and panel data to predict fashion trend forecasts	Zara: *Quantitative analysis of trend forecasting* (2020)
	Computed Identification of Fashion Counterfeits	Computational modeling designed to detect fashion counterfeiting	Alibaba: *Anti-counterfeiting technology* (2017)

Source Developed by the author

similar orders; however, as the fashion industry becomes less predictable, AI simulated algorithms are essential in optimizing this process.

Computer simulations in fashion assortment packing, dispatching, and shipping have also been utilized to model practical manufacturing situations. In one study by Wang et al. (2018), researchers addressed optimizing the packaging of a fashion clothing assortment with collaborative shipping processes. Researchers designed a mixed integer nonlinear programming model to assess a simulated problem: the distribution of nine product variations (i.e., down jackets available in three different sizes and three different colors), with five shipping box configurations, and five shipping trucks available for dispatch. Using a model solver computing software, LINGO 11.0, researchers solved the problem model and generated efficient solutions that are feasible for practical measures. In a practical application, in 2017, the manufacturer Amazon designed a system device that creates on-demand apparel; they were awarded a US patent for this device. The system uses software to collect global apparel orders and designs a plan for efficient order fulfillment within minutes after placement (Nickelsburg, 2017). Coordinating several apparel processes on a vast scale and from various global consumer locations, the patent describes the system's purpose as aiming to increase manufacturing efficiency, potentially replacing apparel factories and production warehouses (Del Rey, 2017). Amazon's actual implementation of the approved patent into a real system, however, is unknown.

Apart from the planning and dispatching measures, but along the lines of apparel product creation, efforts behind the implementation of AI in sewing automation are growing. In the fashion industry, producing quality garments with precision cannot always be achieved through manual labor, where human errors are inevitable. Sewing automation, however, may be key to successfully produce quality apparel products (Abd Jelil, 2018). Several academic studies have assessed the use of robotic systems in manufacturing processes involving sewing (Fung et al., 2011; Kudo et al., 2000; Paraskevi, 2012; Schrimpf et al., 2013); its industry implementation, however, has been slow in adoption. According to scholars, robots are not as agile in dealing with soft materials like textiles due to their stretchy and foldable nature; this may be why robotic implementation is more readily observed in hard material industries, like electronics (DevicePlus, 2018; Schwab, 2016).

In 2016, an inventor Jonathan Zorno created a robot named Sewbo, which was designed to utilize water-soluble thermoplastics to harden fabrics for enhanced sturdiness so they can be easily fed into a sewing machine by a robot. Once a garment is stitched, Sewbo immerses the garment into hot water where it softens and can be sent for finishing like a normal clothing item (Schwab, 2016). Another sewing robot, known as LOWRY, was developed by the company SoftWear Automation. This system uses a highly calibrated machine to detect distortions in fabric for LOWRY to make precise adjustments during the sewing process to assure textile integrity (DevicePlus, 2018). Despite several US patents for LOWRY and the contribution of research toward its development, its actual implementation in textile manufacturing has been limited (DevicePlus, 2018).

Lastly, the most intuitive AI approach when it comes to fashion manufacturing is the case of product quality control and product assurance. Traditionally, garment inspection relies on the trained and experienced eye of human personnel in a manufacturing setting (Abd Jelil, 2018). As it is known, however, workers are prone to committing a range of errors during the inspection process, such as errors arising from fatigue or simple inconsistencies. AI software can afford manufacturers systematically unbiased and calibrated product inspections, such as analyzing sewing defects like puckering (Abd Jelil, 2018) and matching colors accurately through computer vision technologies (Schmelzer, 2019). In one study by Pavlinić et al. (2006), researchers examined the association between fabric elasticity and seam puckering, designing an algorithm that used machine learning to model the relationship and estimate the quality of a garment's seam appearance.

In another study by Kulkarni and Patil (2012), researchers developed a garment defect detection model that used a combination of Gray-Level Co-occurrence Metrics and Probabilistic Neural Networking that incorporated garment texture features to perform online product inspections. Recently, the Chinese equipment developer, Dongguan Yunji Zhihui Technology, launched a high-tech machine designed to precisely control garment quality. Using a computer-vision inspection device and AI as its engine, the machine calculates potential errors on product information when a finished garment is placed in its portal (Varshney, 2021). A summary of AI technologies in the product planning and quality assurance phases of fashion manufacturing is presented in Table 6.1.

AI as an Advisory Role in Fashion Manufacturing

A part of the manufacturing process involves steps in proposing new products and processing their approval (Abd Jelil, 2018). The decisions surrounding these steps are no less complicated than creating and managing product inventory, and they are further subjected to quandaries regarding manufacturing in a volatile fashion market. Thus, computational AI methodologies can be immensely beneficial in creating products, forecasting product trends, and revealing marketplace competitions. This section of the chapter provides both an overview of academic research and practical industry applications of AI as an advisory role in fashion manufacturing.

Fashion Aesthetics and Hyperpersonalization

Aesthetics remain a vital component in the production and manufacturing of fashion products, and cases of AI implementation are observed in the prediction and designing of sensory properties of fashion. The sensation of how garments feel on the skin when they are worn is known as sensorial comfort (Abd Jelil, 2018). In a study by Wong et al. (2004), researchers developed a computing model that predicted fabric performance based on consumers' psychological perceptions of clothing comfort. Through predictive modeling techniques, researchers found that the physical properties of textiles could be used to predict consumers' overall clothing comfort. Since Wong et al.'s (2004) model closely simulates a human sensory experience, manufacturers can implement these findings in cases of raw material selection, although it is not known if they have done so. In a similar study, thermal properties of protective clothing were predicted through computer simulations (Guo et al., 2008). By utilizing a computer-aided design tool, called S-smart, researchers were able to predict and visualize the heat and moisture transfer mechanisms of clothing, highlighting that a simple computational software can be used in the design of protective apparel (Guo et al., 2008), which may be pertinent in manufacturing healthcare or fire safety garments. Fashion brands are also using personalized AI design techniques to closely adhere to consumers' needs. For example, the fashion platform Zalando offers consumers an AI-powered apparel design program to create garments based on their desired colors, textures, and styles (Countants, 2020).

Along these lines, AI has been implemented in product aesthetics through approaches such as 3D rendering and design using human-managed CAD software. Such applications have been widely studied in academic settings and somewhat implemented within the industry. However, a new twist on this application can be seen through the social-media mogul Facebook's new endeavor. Facebook AI recently released details on a new project called Fashion++ that suggests fashion tweaks to users on their social media platforms (Tech@Facebook, 2019). The system is able to differentiate items of apparel on a body and how they are worn by assessing a photographic image. Through a set of sample images of an individual, Fashion++ is able to learn aesthetic preferences (e.g., from understated attire to office-wear) and apply this knowledge to suggest fashion tweaks to users for their outfits. The AI system also generates unfashionable outfits based on machine learning algorithms to educate users on the 'dos and don'ts' of fashion. Facebook's evaluation of Fashion++ deems the project as successful, revealing that participants in the study preferred the AI's fashion suggestions over others (Tech@Facebook, 2019).

The AI system integrated into the Fashion++ project reflects the immense potential for the fashion manufacturing industry; through machine learning, product design can be determined by predicting target market aesthetic preferences. Nike Fit, a sub-brand of the mega-shoe company Nike, recently released a foot-scanning AI that uses smartphone technology to determine the best fit for a consumer's unique foot in combination with their aesthetic preferences. By utilizing machine learning and computer vision techniques, the system recommends shoe sizes and shapes in different styles on users' personal phones (Rejcek, 2019). A shift in the trajectory of on-the-go manufacturing toward 3D printing and personalization is probably also in the works at Nike stores—an AI technology with the potential to further revolutionize the fashion industry, much like Facebook's Fashion++ . A summary of AI technologies implemented in aesthetics and hyperpersonalization of fashion is also presented in Table 6.1.

Forecasting and Competitor Analysis in Production Choices

AI methods in fashion forecasting and analysis have proven to be highly beneficial in providing inventory-related guidance, assistance in smarter production choices, and efficiency improvements to supply chains. Today, several algorithmic approaches have been developed and implemented, challenging traditional forecasting methods, which are expensive and lack accuracy. Indeed, big data-driven forecasting companies seem to be ubiquitous; a quick Google search can retrieve innumerable companies touting AI methods in predicting fashion forecasts. Although some traditionalists in the fashion industry prefer maintaining an intuitive approach, relying on runway shows and observing cultural phenomena to inform forecasts, adopting AI may be critical in enhancing forecast accuracy and manufacturing, especially considering the confounding problem of over-production (Sajja et al., 2021).

In addition to industry AI startups offering forecasting techniques, academic scholars have worked diligently to create AI models designed to predict fashion trends for manufacturing. Newer studies within the last decade have used hybrid models, an approach that includes an element of AI by computationally highlighting patterns in time-series, cross-sectional, and panel data (Liu et al., 2020). In one such research study, Sajja et al. (2021) proposed a forecasting tool in which all stakeholders (i.e., consumers and companies) participate in collective decision-making concerning product design and development. Through multiple pieces of information, such as product lifecycle, pre-season interventions, and geographical explainability, researchers offered a sales analysis model for pinpoint trend forecasting. According to industry providers, several major fashion brands are utilizing a combination of AI and machine learning tools to quickly pinpoint fashion trends, producing fashion pieces faster than their traditional competitors (Countants, 2020). One example includes the fast-fashion global brand Zara, who employs quantitative analysis of their social channel data to predict consumer desires up to one year in advance (Countants, 2020; Heuritech, 2020).

Beyond trend forecasting, in large-scale fashion manufacturing, the counterfeiting of fashion goods can be a serious industry issue. In 2017, the Chinese e-commerce giant Alibaba announced an international alliance with 20 global brands, including Louis Vuitton, to leverage an anti-counterfeiting AI technology (Alizila, 2017). The technology employs algorithms, machine learning, and brand and consumer data to detect fashion counterfeits on the internet. In one month, Alibaba's technology revealed 417 production rackets, valued at 1.43 billion US dollars (the offenders were prosecuted) (Alizila, 2017). Further, it is claimed that the anti-counterfeit AI technology can scan up to 10 million product listings in a day. Fashion industry manufacturers benefit from this kind of technology, which enables them to protect their intellectual property and monitor the sales of fake products. This is one of the countless ways in which AI is able to utilize computer-vision machine learning to assist manufacturers in competitor analysis. A summary of AI technologies implemented in fashion forecasting and competitor analysis is included in Table 6.1.

Conclusion and Future Trends

The integration of AI into the fashion industry offers immense potential and presently can be observed in the streamlining of the production process, factory operation, product creation/management, and advisory of future directions. Figure 6.1 visually summarizes the types of AI in fashion manufacturing, as well as the specific technology subtypes discussed in this chapter. Insights from the afore summary highlight the breadth of AI development from academic and theoretical standpoints. However, extensive application of AI in the industry setting is essential

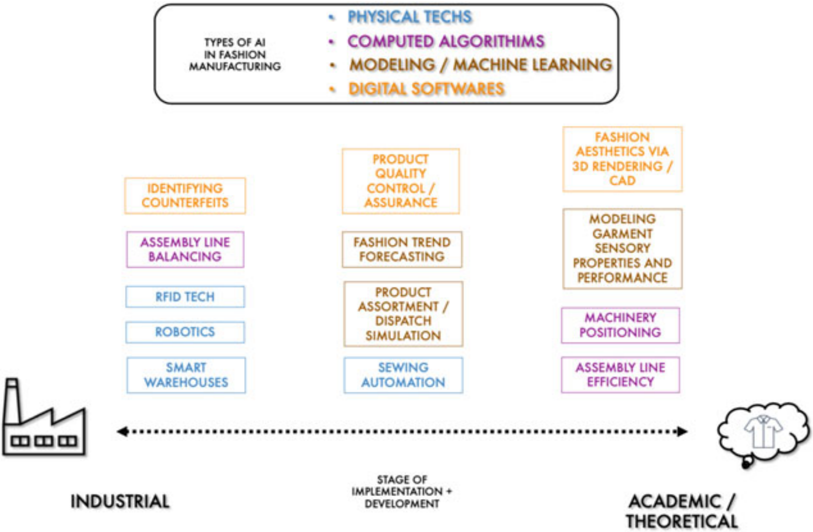

Fig. 6.1 Types of AI in Fashion Manufacturing and Approximation of Implementation between Industrial and Academic/Theoretical Stages (*Source* Developed by the author)

for the fashion industry to progress. Figure 6.1 demonstrates the position of each technology on a continuum of implementation and development between industrial and academic/theoretical stages. An increase in AI research within the last decade can be observed within the academic realm (Giri et al., 2019); this momentum is not fully reflected in its industry applications. With global digitalization pervading almost all consumer industries, the fashion industry must maintain a strong AI presence. Although this lack of momentum could mainly be due to the exorbitant costs associated with the implementation of AI, future cost-benefits can be predicted much like in environmental and sustainable efforts.

Indubitably, slow implementation of AI technologies is particularly associated with significant costs at the moment, and manufacturers may not find the upfront costs worthy, provided many unknowns surrounding the application of AI and its effects. As shown in Table 6.1, there are some specific challenges, however, associated with AI technologies that are beyond upfront costliness. For example, although RFID tags are an affordable form of AI that retailers can use in manufacturing, large fashion retailers with multiple manufacturers find it difficult to streamline the implementation of RFID among many of their facilities (Hensel, 2020). That is, with hundreds of different apparel suppliers, getting all of them to implement RFID tags is a challenge, and mixed-implementation may defeat the purpose of inventory use of RFID in-stores (Hensel, 2020).

Other challenges regarding the lagging implementation of AI in fashion manufacturing have to do with the materials of fashion itself. As aforementioned, although sewing automation potentially affords manufacturers quality precision beyond human means, the malleable structure of textiles makes it difficult for machines to handle delicately (Schwab, 2016). The implementation of 3D rendering of apparel items also poses challenges. Although 3D printed apparel potentially affords the manufacturing world exciting opportunities, the current availability of 3D materials used for printing is limited. Further development is needed in printing materials that exhibit quality, fabric-like finishes (Iribarren, 2018).

One potential solution for some of the afore challenges is for manufacturers to collaborate with academic institutions. Collaborations could potentially mitigate costs while advancing the knowledge and use of and AI in the field. For instance, research for the development of SoftWear Automation's robotic sewing machine commenced at Georgia Tech's Advanced Technology Department Center, but later, was funded by the

Walmart Foundation, a billion-dollar industrial player (DevicePlus, 2018). Collaborations between AI researchers, scholars, and industry experts are critical in advancing AI knowledge and providing industry managers with a way to learn and implement these novel technologies. Fashion companies forming alliances with AI startups (such as the collaboration between Nike and Celect), or even organizing teams dedicated toward advancing AI methodologies in production, which is what Amazon chose to do, are strongly encouraged in this pursuit.

Further issues and challenges impede the progression of AI implementation in fashion manufacturing. Historically, fashion manufacturers utilized traditional means to manage their inventory and bookkeeping. Although there is pressure to evolve out of such traditional processes in the current e-commerce landscape, cybersecurity may eventually become a concern, provided an apprehension regarding the lack of security of consumers' personal transactions and companies' finances. Over the last decade, blockchain technology has garnered significant attention and experienced remarkable acceptance worldwide. It may serve as an encrypted global solution for bookkeeping and ledgering in the inventory manufacturing environment.

Moreover, current AI applications, especially those in soft computing or communication between devices in an IoT environment, require *large* data sets that must synchronize with other technologies and the generated data (e.g., in the case of achieving a completely digitized environment, such as a smart warehouse). Actual tasks in a real IoT environment where warehouse manufacturing occurs are far more complex and unpredictable than the formulated scenarios in academic research for the purpose of experimentation (Liu et al., 2018), raising doubts concerning the integrity of the information afforded by the AI literature so far. The large and variable amount of data that may be available for simulation in an academic scenario is not always accessible to industry workers in actual factory settings. Thus, AI approaches must progress toward more unsupervised learning techniques in training unlabeled data for AI modeling (Abd Jelil, 2018).

Even with the unique challenges of integrating AI into fashion manufacturing, the potential of AI affords the industry with inspiring opportunities for the future if there is significant progress. If academic scholars and industry experts are encouraged to collaborate on furthering this pursuit and tackling practical challenges that afflict manufacturing, the possibilities afforded by AI and the subsequent creation and distribution of fashion products are boundless. If advances in the applications of AI are accomplished in the near future and at superior standards, certain theoretical and practical questions may be important for scholars and manufacturers to consider. In an effort to help conceive best practices in the implementation of AI in fashion manufacturing, this chapter concludes with some theoretical scenarios and questions for the industry to consider.

- In a future where fashion products may be completely manufactured through robotics, does automatization compromise creative integrity? If so, which specific technologies challenge the notion of creative authenticity?
- Would mass-automatization of fashion create a counter market of entities bucking AI integration in the pursuit to preserve the essence of fashion? What would this market look like and how would it be addressed by fashion leaders around the world?
- What does automation of AI in retail afford the human workforce and how can we sustain manual labor (either by preserving existing jobs or creating new ones) while progressing Industry 4.0?

Sources of Further Information

For additional information and news regarding current industry applications of AI in fashion manufacturing, please refer to the following collection of resources.

- **Hyperpersonalization:** As an essential development in AI fashion manufacturing, personalized marketing is witnessed in the recent developments of Facebook's Fashion++ digital style guide (https://ai.facebook.com/blog/building-ai-to-inform-peoples-fashion-choice/) and Nike's sub-brand Nike Fit (https://news.nike.com/news/nike-fit-digital-foot-measurement-tool), which utilizes consumers' smartphones for shoe customization, considering their fit and style.
- **RFID Technology:** The rate of RFID implementation in fashion manufacturing is growing, with apparel companies teaming up with leading RFID partners, such as Zebra (https://www.zebra.com/us/en.html), Alien Technologies (https://www.alientechnology.com), Avery Dennison (https://www.averydennison.com/en/home/technologies.html), and RFID4U (https://rfid4u.com).

- **Robotics:** Amazon's patent on-demand clothing manufacturing system uses a combination of computerized software and automation, including textile printers and cutters to design, create, and fulfill the customers' apparel orders within a single system (https://www.vox.com/2017/4/18/15338984/amazon-on-demand-clothing-apparel-manufacturing-patent-warehouse-3d).
- **Sewing Automation:** Although the automatization of sewing garments is concomitant with challenges in its mass production, several seminal robotic technologies stand out, like in the cases of Sewbo (https://www.sewbo.com/) and SoftWear Automation (https://softwearautomation.com).
- **Smart Warehouses:** TGW Living Logistics is a leading global company that designs and implements smart warehouse solutions for fashion manufacturers (https://www.tgw-group.com/us/industries/fashion-apparel).

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CHAPTER 7

The Application of Augmented Reality Technology in Apparel Design: A Case of "Plaid Waltz"

Seoha Min and Hye Young Kim

Abstract Augmented reality (AR) technology has been applied to the apparel industry, but its applications in apparel design have not been comprehensively discussed in the academic field. This chapter demonstrates the way AR technology can be applied to apparel design through a case study of "Plaid Waltz." This innovative design of "Plaid Waltz" utilizes AR technology to enhance and increase consumer interaction by reinforcing sensory experiences through a blend of virtual visuals

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and auditory stimuli. Through an AR application called "Plaid Waltz," consumers can view virtual animations of geometric 3D shapes of recognized patterns in the physical plaid on the dress and hear waltz music accompanied with animations. This case study provides insights into its potential for designers who are inclined to apply AR technology to their design.

Keywords Augmented reality · Multisensory design · Apparel design · Virtual technology

INTRODUCTION

Carmigniani et al. (2011) assessed the state of augmented reality (AR) to define the concept and address its applications. They defined AR as "a real-time or indirect view of a physical real-world environment that has been enhanced/augmented by adding virtual computer-generated information to it" (p. 342). AR allows its users to experience not only the computer-generated virtual world but also their tangible surroundings simultaneously. Carmigniani et al. (2011) further indicated that AR technology improves the "users' perception of and interaction with the real world" (p. 342). Affirming their assertion, AR technology has garnered significant attention from industry practitioners and academic researchers in the field of clothing and textiles.

According to MarketandMarkets (2018), the AR industry is estimated to reach 60.55 billion US dollars by 2023 globally, and the retail market is expected to contribute to the growth of AR substantially. In this respect, Caboni and Hagberg (2019) reviewed AR technology in the context of retailing and discussed its definitions and applications within this context. They asserted that AR technology is a notable digital technology that facilitates the changes in a typical retail store, where the traditional and digital store elements will synchronize. To utilize AR technology, the inclusion of the concept of a visual marker that a mobile device can recognize is imperative. By applying a visual marker, such as a QR code, numerous retailers have incorporated AR into their product package design to attract consumers' attention. For example, an Australian wine retailer, 19 Crime, implemented AR into the label of their wine. Once consumers download their mobile application and view the label through it, they are able to watch the prisoner in the label talk about his/her story; this has boosted their sales significantly (Stone, 2017). In addition to this example, there are a number of retailers who attempt to include AR into their product design to attract consumers' attention and to provide detailed information about the product. AR technology becomes more relevant to the retail sector in the age of COVID-19 because it allows consumers to try on products online without visiting retail stores.

Despite its numerous applications in the field of retailing, there are no sufficient studies regarding the applications of AR in the field of apparel design. Only a few designers attempted to utilize AR in their apparel designs (Häkkilä et al., 2017; Min & Kim, 2018; Min & Kim, 2019a; Min & Kim, 2019b). Häkkilä et al. (2017) appended several signals related to historical information to two garments and integrated AR into these signals. Min and Kim have collaborated to create several AR-integrated clothing, such as *Trapped in Beauty* (Min & Kim, 2018), *Plaid Waltz* (Min & Kim, 2019a), *Rhythmus 2019* (Min & Kim, 2019b); however, the method of applying AR to apparel design has not been comprehensively demonstrated yet. To this end, a detailed demonstration of ways to apply AR to apparel design, focusing on the case of *Plaid Waltz*, has been provided in this chapter. AR technology was applied to *Plaid Waltz* to enhance users' multisensory experience with the dress. This case study provides valuable guidance to design practitioners who wish to apply AR technology to their designs, as well as design educators interested in incorporating the concept of AR technology in their classrooms.

Multisensory Design process of *Plaid Waltz*

Plaid Waltz was designed by the authors and presented at the annual mounted design exhibit at the International Textiles and Apparel Association Conference in 2019 (Min & Kim, 2019a). *Plaid Waltz* was designed to maximize a user's multisensory experience through AR technology. According to Mete (2006), a sensory design includes a product that is experienced through the physical senses: visual, auditory, tactile, olfactory, and gustatory. The main purpose of a sensory design is often users' sensory experience itself (Mete, 2006) as it could not only evoke their aesthetic pleasure, but also help form relative, expressive, semantic, and symbolic implications for them (Schifferstein & Desmet, 2008). A sensory design that involves a user's multiple sensory system refers to a multisensory design, which often enriches users' product experience if all sensory impressions of the design contribute toward amplifying a single chosen expression of the product (Schifferstein, 2011).

Plaid Waltz is designed to evoke a user's multisensory experience by utilizing AR technology. To demonstrate, the authors developed a prototype based on Schifferstein's (2011) multisensory design process, consisting of the following eight stages: (a) Selecting the target expression, (b) conceptual exploration, (c) sensory exploration, (d) sensory analysis, (e) multisensory mind map, (f) user-interaction scenario, (g) model making, and (h) multisensory presentation (Fig. 7.1). In the first stage, the selection of the target expression, "unexpected pleasure" was selected as the main expression of the design. In the stage of conceptual exploration (Stage 2), waltz, one genre of dance performed by a couple three times was explored, owing to its association with the theme. The utilization of AR technology in the design to communicate the theme, unexpected pleasure, was also explored. As AR applied to the dress can be only detected by a mobile application, the AR elements can provide unexpected elements to the design. In the stage of sensory exploration/sensory analysis (Stages 3 and 4), the authors explored how waltz would feel, sound, smell, and look. For example, information regarding

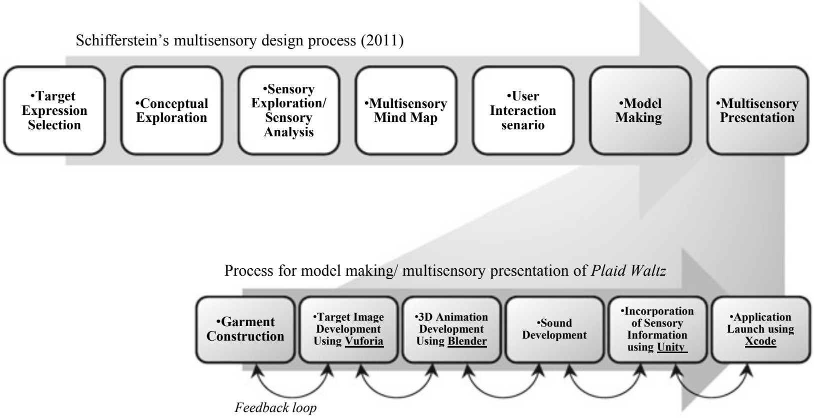


Fig. 7.1 Prototype Development Process (*Source* Developed by the authors using Schifferstein's (2011) multisensory design process)

waltz music, dance movement, and crisp fabrics/colors of waltz dress were collected and analyzed.

In the stage of the multisensory mind map (Stage 5), all the information collected in the previous stages was organized and a prototype based on the accumulated information was ideated. In the stage of the user-interaction scenario (Stage 6), the senses that were stimulated when a user interacts with the product were assessed. During the simulation, it was decided that the focus would be on the response of the visual, auditory, and tactile senses elicited by the design. In the stage of model making (Stage 7), the authors created a physical prototype using pattern-making method. To communicate the theme of the dress, five different plaid fabrics were carefully chosen and cut with different grainlines. Then, AR mobile application, entitled "*Plaid Waltz*," was developed by utilizing AR tracking and registration techniques through Vuforia (AR software development kit), Blender (3D animation software), and Unity (game engine software). After the dress creation, the authors published the mobile application utilizing Xcode (integrated development environment for iOS apps) in the stage of multisensory presentation (Stage 8). In the prototype development process, the authors went back and forth between the stages to develop an application that amplifies a user's multisensory experience (Fig. 7.1). The stages of model making and multisensory presentation are specifically demonstrated in the following sections.

Garment Construction

To create a dress, pattern-making techniques were used. Based on basic pattern blocks, patterns of the dress were created and a test garment was constructed. It was proven that the measurements originally taken and transferred into the pattern pieces were precise by assessing the garment fit. To communicate the inspiration of the dress, five different plaid fabrics were carefully chosen and cut with different grainlines. Then, facings, seven buttons, and a waistband were attached to the dress. After the garment construction, the Vuforia software was utilized to develop target images that stimulated 3D animation in the AR mobile application.

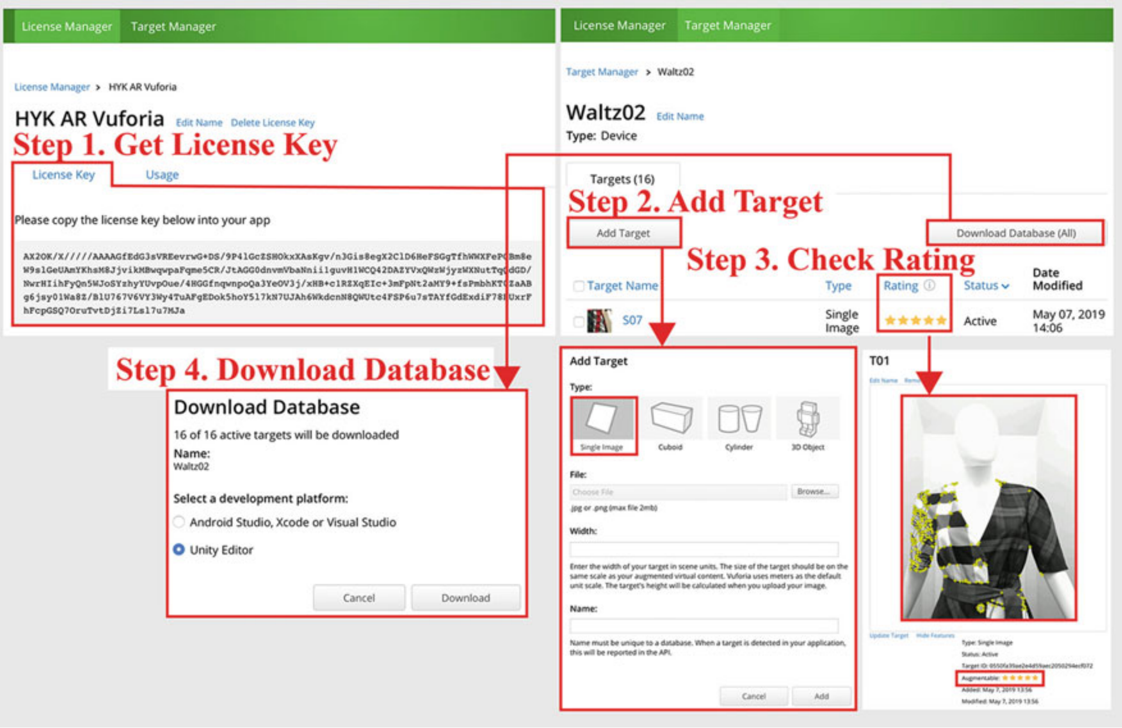
Target Image Development Using Vuforia

Vuforia is an AR software development kit for mobile devices that enables the development of AR mobile applications (Sing et al., 2020). Vuforia utilizes computer vision technology to recognize and track visual markers and further assist in displaying 3D virtual objects in the Unity software (Sing et al., 2020). The way a license key and visual markers in the interface of Vuforia were generated is demonstrated in Fig. 7.2. First, a license key to register visual markers in the Unity software was required. In order to do so, the authors created an account on the Vuforia developer website (https://developer.vuforia.com) and received a license key. The license key was utilized in the Unity software to configure the database created in Vuforia at the later step.

Second, visual markers that were recognizable by the Vuforia software were created. Sixteen photographs of the dress, *Plaid Waltz*, were taken in various angles and imported to a database in Target Manager in the Vuforia website. When importing the images, the format of the images had to be in the 8- or 24-bit PNG or JPG format, with less than 2 MB size and the RGB or grayscale was required for the JPG format (no CMYK) to upload the image (Step 2 in Fig. 7.2). Third, the authors ensured that 16 visual markers received high ratings from the Vuforia software. The Vuforia software analyzes visual markers and evaluates whether the visual markers can be readily recognizable by a mobile device. The highest score that a visual marker can receive in the Vuforia software is 5 stars and it was ensured that all the visual markers received higher than 4 stars from the software. To achieve the high ratings, each image had to be rich in detail, display high contrast, and not have repetitive patterns. If any visual marker received 3 stars from the software, the photo of the dress was captured again and re-uploaded to the Vuforia software until it received a rating higher than 4 stars from the software (Step 3 in Fig. 7.2). Once all the visual markers received high ratings from the software, the database containing all the visual markers was downloaded. When downloading the database, Unity Editor was chosen for a development platform and the database was imported to Unity at a later step.

3D Animation Development Through Blender

After developing visual markers in the Vuforia software, 3D animations were created in the 3D modeling software, Blender. To create 3D animation, designers can utilize any kind of 3D animation software, such as Autodesk, Maya, Blender, and Rhino (Gu & Liu, 2019). Blender was chosen for the *Plaid Waltz* creation due to our expertise with the software. Further, the software is free of cost. Using Blender, 16 different animations were created, which matched with the 16 visual markers.



License Manager > HYK AR Vuforia

HYK AR Vuforia Edit Name Delete License Key

Step 1. Get License Key

License Key Usage

Please copy the license key below into your app

AX2OK/X/////AAAAGfEdG3sVREevrwG+DS/9P4lGcZSHOkxXAsKgv/nJGis8egX2ClD6HeFSGgTfhWWXFeP Bm8e
W9slGeUAmYKhsM8JjvikMBwqwpaFqme5CR/JtAGG0dnvmVbaNniilguvHlWCQ42DAZYVxQWzWjyzWXNutTq dGD/
NwrHIihFyQn5WJoSYzhyYUvpOue/4HGGfnqwnpoQa3YeOV3j/xHB+clRZXqEIc+3mFpNt2aMY9+fsPmbhKT ZaAB
g6jsy0lWa8Z/BlU767V6VY3Wy4TuAFgEDok5hoY5l7kN7UJAh6WkdcnN8QWUtc4FSP6u7sTAYfGdExdiF78 UxrF
hFcpGSQ7OruTvtDjZi7Lsl7u7MJa

Step 4. Download Database

Download Database

16 of 16 active targets will be downloaded

Name:
Waltz02

Select a development platform:

○ Android Studio, Xcode or Visual Studio

● Unity Editor

Target Manager > Waltz02

Waltz02 Edit Name

Type: Device

Targets (16)

Step 2. Add Target

Step 3. Check Rating

☐ Target Name	Type	Rating ⓘ	Status ⌄	Date Modified
☐ S07	Single Image	★★★★★	Active	May 07, 2019 14:06

Add Target

Type:

File:

.jpg or .png (max file 2mb)

Width:

Enter the width of your target in scene units. The size of the target should be on the same scale as your augmented virtual content. Vuforia uses meters as the default unit scale. The target's height will be calculated when you upload your image.

Name:

Name must be unique to a database. When a target is detected in your application, this will be reported in the API.

T01

Type: Single Image

Status: Active

Augmentable: ★★★★★

Added: May 7, 2019 13:56

Modified: May 7, 2019 13:56

Fig. 7.2 Vuforia Interface (*Source* Developed by the authors)

The geometric shapes of the plaid fabrics were analyzed and then used to create the 3D animations, which will be displayed virtually in the developed AR mobile application.

The way 3D animations were created in the interface of Blender is presented in Fig. 7.3. First, various 3D cubes in Blender were generated (Step 1 in Fig. 7.3). The 3D cubes were inspired by the rectangular shapes and various colors of the plaid fabric (Step 2 in Fig. 7.3). Then, the texture with a color that was similar to the plaid fabric was applied to the 3D cubes. 3D animations were then produced by utilizing Transform, which enabled the cubes' transformation in different locations, angles, and scales. The final 3D animation lasted 10 s, with 24 FPS (frames per second). In Fig. 7.3, the yellow bars indicate keyframes, which record how to set the cubes' location, angle, and scale, while the green bar indicates the present moment of animation (Step 3 in Fig. 7.3). Finally, the animation was saved in the Blender file (B02.blend) and was imported to Unity at a later step.

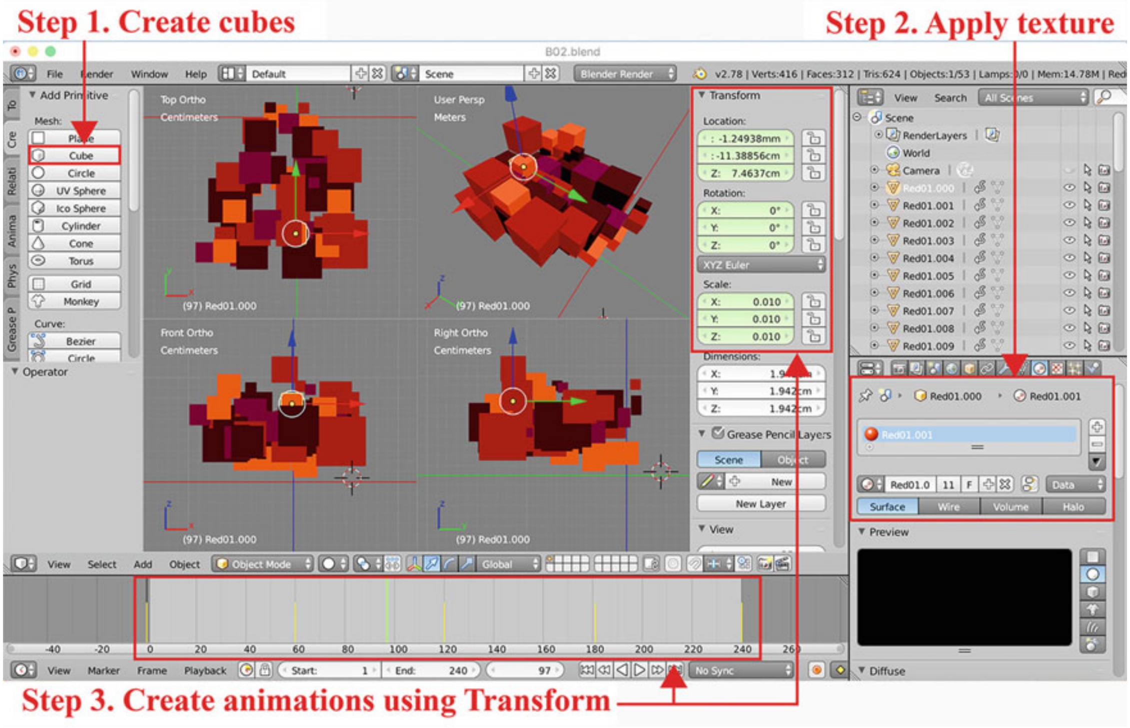
Sound Development Using the Freesound Resource

To develop sounds for the AR application, a free sound resource available online was utilized. Waltz music was downloaded from the Freesound website (https://freesound.org), a non-profit organization that offers a collaborative database of licensed sounds. The downloaded waltz music was edited on the website and extracted in an MP3 format. A sound can also be any audio recorded by a designer, depending on the purpose of the design. As the purpose of the dress, *Plaid Waltz*, was to address the multisensory experiences with the AR application, waltz music was considered appropriate for the purpose. The developed sound was imported to Unity to play sounds along with 3D animations.

Incorporation of Developed Sensory Information Utilizing Unity

After developing 16 visual markers using Vuforia, 16 3D animations through Blender, and waltz music from the Freesound website, all the sensory information was incorporated through Unity, a software which is generally utilized to develop video games. By utilizing Unity, an interactive mobile application was created (Linowes & Babilinski, 2017).

Figure 7.4 demonstrates how an interactive AR application was created in the interface of Unity. First, the 16 visual markers were imported to


Step 1. Create cubes

Step 2. Apply texture

Step 3. Create animations using Transform

B02.blend

v2.78 | Verts:416 | Faces:312 | Tris:624 | Objects:1/53 | Lamps:0/0 | Mem:14.78M | Red

Transform

Location:
X: -1.24938mm
Y: -11.38856cm
Z: 7.4637cm

Rotation:
X: 0°
Y: 0°
Z: 0°

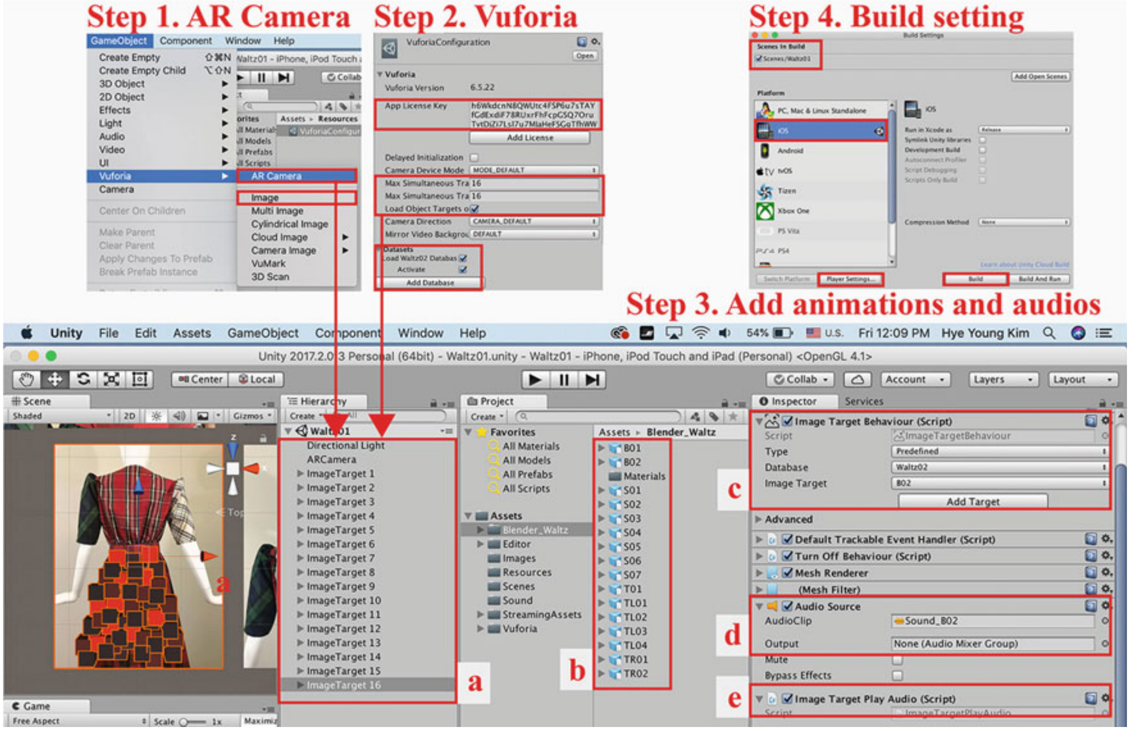
XYZ Euler

Scale:
X: 0.010
Y: 0.010
Z: 0.010

Dimensions:
X: 1.942cm
Y: 1.942cm
Z: 1.942cm

Start: 1
End: 240
97

Fig. 7.3 Blender Interface (*Source* Developed by the authors)



Vuforia Version 6.5.22
App License Key h6WkdcnN8QWUtc4FSP6u7sTAY fGdExdiF78RUxrFhFcpGSQ7Oru TvtDiZi7Ls17u7MlaHeFSGqTfhWW
Delayed Initialization ☐
Camera Device Mode MODE_DEFAULT
Max Simultaneous Tra 16
Max Simultaneous Tra 16
Load Object Targets o ☑
Camera Direction CAMERA_DEFAULT
Mirror Video Backgrou DEFAULT
Load Waltz02 Database ☑
Activate ☑

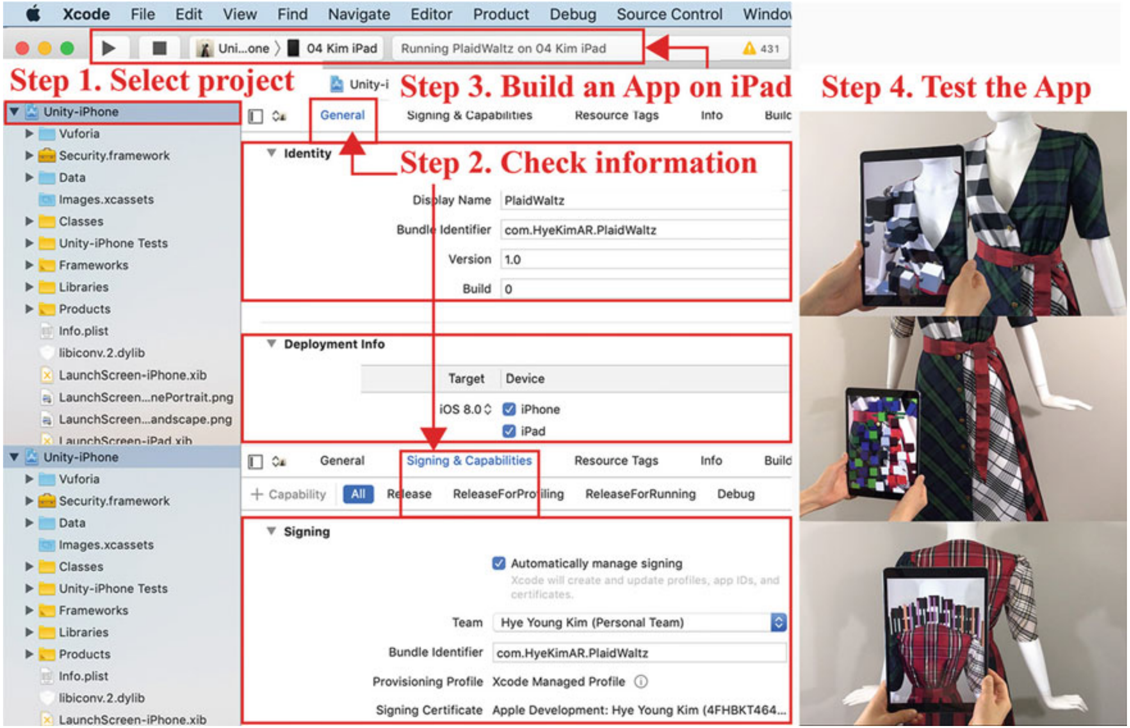
Run in Xcode as Release
Symlink Unity libraries ☐
Development Build ☐
Compression Method None

Script ImageTargetBehaviour
Type Predefined
Database Waltz02
Image Target B02
AudioClip Sound_B02
Output None (Audio Mixer Group)
Mute ☐
Bypass Effects ☐

Fig. 7.4 Unity Interface (*Source* Developed by the authors) the AR camera section in the Unity software (*Unity* → *Game Object* → *Vuforia* → *AR Camera/Image*) (Step 1 in Fig. 7.4). Second, the Vuforia settings were configured in Unity and the database containing the 16 visual markers was imported, which were downloaded from the Vuforia software (*Unity* → *Asset* → *Import Package* → *Custom Package*). The authors then went to Vuforia Configuration in the AR camera section, added the license key created in the Vuforia software, changed the target number to 16, and uploaded and activated the database (Step 2 in Fig. 7.4). The next step was to import Blender files (3D animations) and append 16 animations to the 16 visual markers. This process requires scripts, which allows the software to detect visual markers, play the associated animations on a loop during the detection, and stop the associated animation if the visual markers are not detected anymore. Sixteen different Waltz sounds were also imported and added to the visual markers. This process also requires a script to play the associated sound when the visual markers are detected (Step 3 in Fig. 7.4). After the visual markers, 3D animations, and sounds were imported to Unity, an AR iOS application was set up as the final step (*Unity* → *File* → *Build Setting*) (Step 4 in Fig. 7.4).

Launching the Application Using Xcode

Xcode is an integrated development environment (IDE) for macOS containing a suite of software development tools (Feiler, 2018). Xcode enables users to build the AR mobile application directly on their smartphones or tablets to test and publish the AR application to the Apple Store. Figure 7.5 demonstrates how the AR application was built on the iPad and tested in the interface of Xcode. First, in Xcode, the authors launched a project titled *Unity-iPhone.xcodeproj*, which was formulated in Unity, and selected Unity-iPhone in the Xcode software (Step 1 in Fig. 7.5). Second, the authors ensured that the information is accurate in the section of General and Signing & Capabilities in the software (Step 2 in Fig. 7.5). Third, an iPad was connected to a computer and an AR mobile application was built on the iPad (Step 3 in Fig. 7.5). Finally, the iPad was disconnected from the computer, the AR application was opened on the iPad and permitted to utilize a camera by the AR application. When the iPad recognized any visual markers in the dress through a camera, the iPad played the associated 3D geometric animation and the associated sound of the waltz music on the live view of the camera (Step



Identity

Display Name: PlaidWaltz
Bundle Identifier: com.HyeKimAR.PlaidWaltz
Version: 1.0
Build: 0

Deployment Info

Target: iOS 8.0
Device: ☑ iPhone ☑ iPad

Signing

☑ Automatically manage signing
Xcode will create and update profiles, app IDs, and certificates.

Team: Hye Young Kim (Personal Team)
Bundle Identifier: com.HyeKimAR.PlaidWaltz
Provisioning Profile: Xcode Managed Profile
Signing Certificate: Apple Development: Hye Young Kim (4FHBKT464...

Fig. 7.5 Xcode Interface and AR Application Testing (*Source* Developed by the authors)

4 in Fig. 7.5). Further details on how the 3D objects animate with the waltz music are shown in the YouTube video the authors published in 2019 (Min & Kim, 2019c).

CONCLUSION AND FUTURE TRENDS

In this chapter, the detailed process to create apparel designs with AR by utilizing the AR tracking and registration techniques through Vuforia (AR software development kit), Blender (3D animation software), Unity (game engine software), and Xcode (integrated development environment for iOS apps) was discussed. The software was self-taught by one of the authors and went through several trials to create the AR for the dress. As a result, the developed animations and sounds were successfully played through the developed AR application if a user saw the visual markers in the dress utilizing the application (Fig. 7.6). The visual, tactile, and auditory stimuli of the dress were considered as relevant to the main inspiration, Waltz. By beholding the dress with plaid fabrics, a user could appreciate the crisp texture and the rusting sounds from the fabrics of the dress. The user also visualized the rhythmical movement of waltz by viewing the unique combination of the five different plaid fabrics. By viewing the dress through the AR mobile application, the user could hear Waltz music and see numerous geometric 3D shapes moving along with it. In this respect, the user's multisensory experience with the dress was amplified by AR technology.

The apparel design with AR has several implications. First, clothing with AR could maximize users' multisensory experience with clothing, such as in the case of *Plaid Waltz*. According to Shifferstein and Desmet (2008), all sensory information users receive from a product, contributes to their product perception, cognition, experience, and behavior. They further asserted that a multisensory design approach is required to build a strong brand image where all the senses are stimulated toward users' consistent experiential benefit (Shifferstein & Desmet, 2008). As the design of *Plaid Waltz* and its AR communicate the same inspiration by stimulating a user's multisensory system, the message of the dress is reinforced when perceived by the user. Therefore, clothing with AR could reinforce an image and message that the designer would like to communicate by amplifying users' multisensory experience with clothing.

Second, clothing with AR could provide important information to viewers. For instance, clothing with AR could help visitors and event

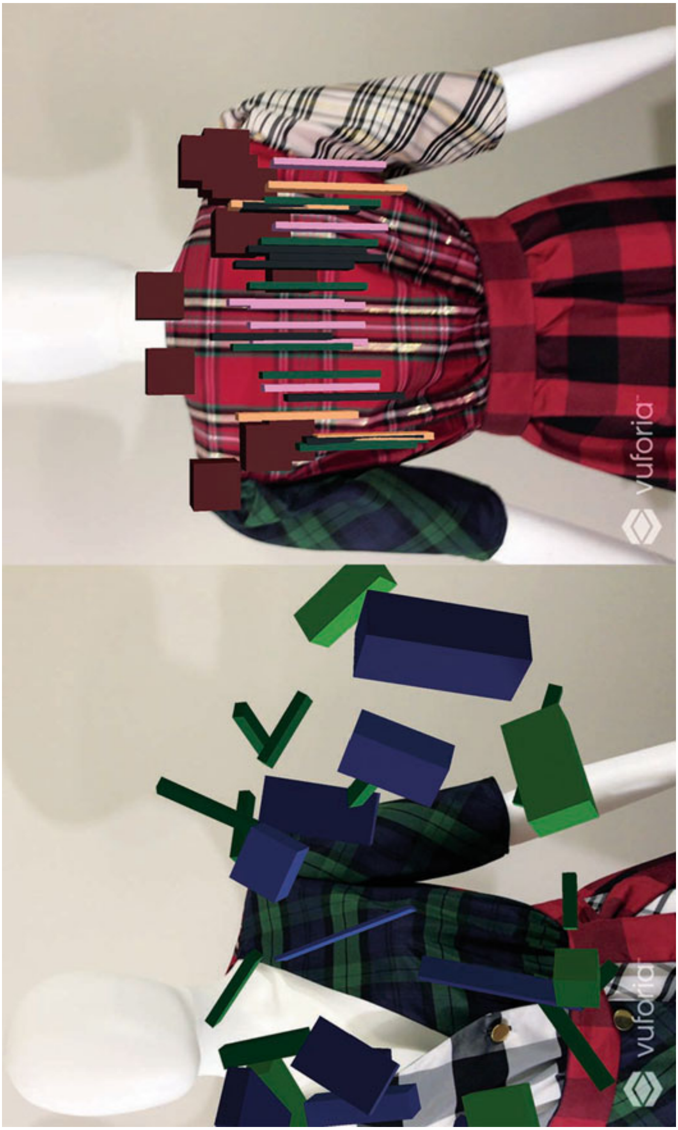


Fig. 7.6 Final AR Dress Prototype (*Source* Developed by the authors)

organizers in a certain event. If the event organizers and the staff wear a t-shirt with a visual marker attached to it, the event participants can scan the visual marker and browse detailed information concerning the current and the next event agenda through the application on their mobile device (Häkkilä et al., 2017). In this way, the event participants can easily find information about the event through clothing with AR without asking questions to the staff. In this regard, when AR is applied to apparel, it could provide the necessary information to viewers in a certain context.

Furthermore, AR technology could compel users to be attentive to a care label of clothing. If users understand the care label properly and wash clothing properly, it will eventually reduce the environmental impact of laundering and further increase the clothing lifespan (Gwilt & Rissaene, 2012). A care label often includes the composition of materials and laundry symbols to indicate the way in which clothing items can be washed, dry cleaned, or ironed. However, many consumers tend not to pay attention to laundry symbols or misunderstand the symbols because they are small and do not clearly describe their implications, such as a circle for dry clean and a triangle for bleach (Workman & Choi, 1999). Therefore, a more detailed and user-friendly care label is recommended, and AR technology could help facilitate this effort. For example, designers could communicate more detailed care information of their clothing through AR technology. If users view the care label from the AR application on their mobile device, a more detailed information of the care label can be presented and explained through the AR contents. This will help users better understand how to care clothing properly, which will eventually benefit the environment. In addition, a care label with AR can inform users about how much carbon dioxide has been consumed in the production of clothing. This will help users care the clothing item for a prolonged period of time and further elicit sustainable consumer behaviors and initiatives.

In addition, clothing with AR could help users express their identity in an intriguing manner. For example, a message printed on a t-shirt is often used to communicate users' identity or their aspirations as a part of the younger generation (Chiluwa & Ajiboye, 2016). Within the same context, if a message is added to clothing by AR technology, viewers can view the message through their mobile device. This is a less direct way to deliver the message to viewers compared to the printed message on a t-shirt. For instance, the dress entitled *Trapped in Beauty* is composed of a black dress attached with patches of various lip shapes, which are visual targets recognized by the AR application (Min & Kim, 2018). If viewers see the lip shapes through the AR application, the lips start communicating how the perception of our appearances affects our identity, confidence, and self-esteem. This work expects the viewers to hold open dialogues about the way we judge our and others' appearance. Just like this example, AR technology will help users communicate various messages with their AR-embedded clothing.

Finally, this case study provides important guidance to educators who have interests in addressing AR technology in their design curriculum. Existing literature indicates that students who had exposure to AR technology in their learning process achieved higher success and acceptance in their learning outcomes, enabling them to focus on the functional, aesthetic, and creative aspects of apparel (Elfeky & Elbyaly, 2021). Therefore, educators who wish to enhance their students' design skills and creativity could incorporate this AR technology demonstration into their classroom. Before incorporating AR technology into their curriculum, educators need to ensure that their students have sufficient knowledge pertaining to garment construction and 3D modeling software so that students can focus specifically on AR elements in the classroom.

There are several suggestions for future research. Design practitioners have attempted to collaborate with experts in the field of computer science to introduce the concept of AR technology into their work, as well as generate a variety of creative ideas. However, Milovanovic et al. (2017) indicated that there are very few software tools supporting designers' idea generation stage in the design process. They indicated that there existed no solutions on the market that were specifically designed to enhance the generation of creative ideas for design practitioners who have limited expertise in the computer sciences. Because of their limited expertise, they would find it challenging to apply AR to their design despite its numerous benefits.

As a matter of fact, the authors have utilized four different software to apply AR to the *Plaid Waltz* design and went through countless trials and errors working with different software. This implies the necessity of new software that integrates various functions of the four software utilized in this design so that design practitioners can add AR to their design efficiently. Software that analyzes the target image, creates 3D modeling, incorporates the stimuli, and publishes the completed application will make this process more accessible to designers who wish to apply AR to their design.

Lastly, this case study focused on enhancing multisensory experiences of a dress through AR technology. Despite the literature discussing various values of AR technology for consumers and retailers (Caboni & Hagberg, 2019), there is no study exploring how consumers perceive and behave toward AR-applied apparel design. In addition, apparel is closely tied to the geometry of human body and characteristics of movement postures of the targeted users. Thus, designers need to consider various human factors in the design process. However, such aspects were not taken into consideration in the current case study. To broaden the understanding of AR technology and apparel design, empirical studies on consumers' preference and their human factors associated with AR-applied apparel design will be beneficial. Further exploration of other applications of AR technology in apparel design is also encouraged.

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INDEX

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