



Undergraduate Programme

Submitted by: u1823072

Date Sent: 24/03/2022

Module Title: Digital Innovation Project

Module Code: IB3L60

Date/Year of Module: 2022

Submission Deadline: 24/03/2022

Word Count: 3745

Number of Pages: 16

1. Introduction

The fashion industry has been in a continuous change over the past few decades due to the rise of consumerism, but in recent years, it is being fundamentally reshaped by the 4th Industrial Revolution, as technologies advanced and people's attitude towards sustainability is changing (Jin and Shin, 2021)¹. The industry has been developing on all the levels, from the design stage to production and distribution, with digital innovations emerging in all of these aspects, reforming these processes. While these can be classified as market pull innovations, as they come as a result of customers' need for more customizable, rapid and greener products and experiences (Gazzola *et al.*, 2020)², it cannot be overlooked how they have become a paradigm shift for the fashion industry, changing completely the dynamics compared to even 10 years ago. Therefore, this paper will determine how the digital innovation in fashion have shaped and will shape the industry, by analyzing its past development trajectory, the impact it has had on the current market and the possible future outlook. It will investigate the digital drivers of the industry from a value chain perspective, from the design stage until the distribution before the products interact with the customers.

2. Terminology

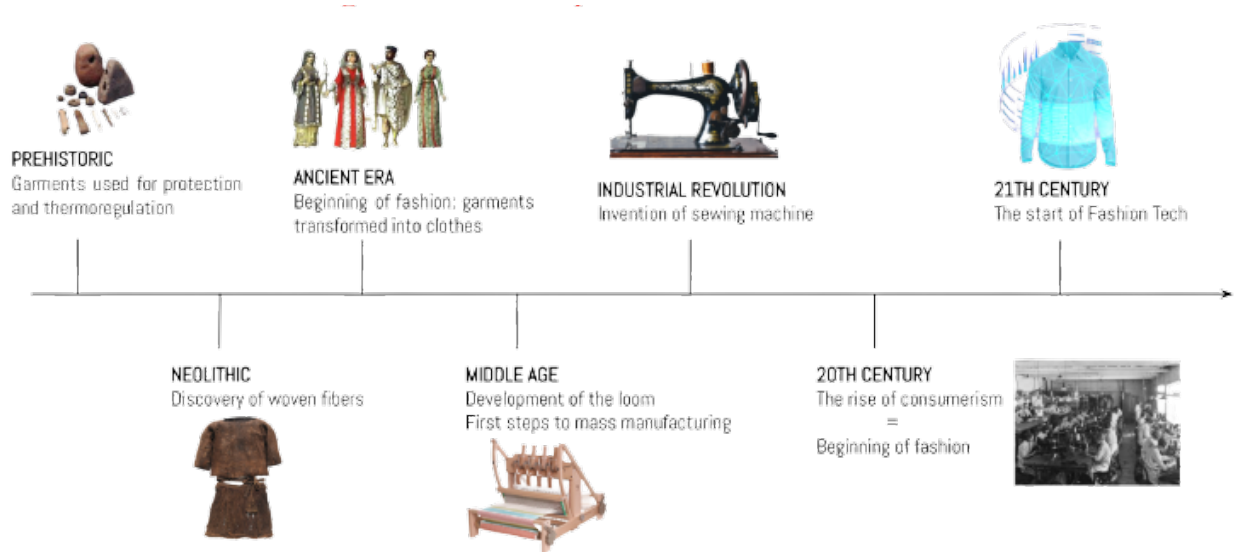
This paper tackles the impact of digital innovations on the fashion value chain, while bringing into discussion numerous concepts specific to the clothing industry. Thus, down below there are some valuable definitions which will offer the possibility of a better understanding of how technological advancements have shaped the fashion sector.

Fashion value chain refers to the activities that are needed to create a final product, including the conception stage, design, production and ending with distribution (Tardi, 2020)

Circular economy refers to a business model which focuses on achieving sustainable goals by promoting reusing, repairing, refurbishing and recycling practices in the whole supply chain (www.europarl.europa.eu, 2015).

Fast fashion refers to apparel that has a fast production time and low cost, focusing more on providing mass volumes rather than qualitative and ethically produced products (Merriam-Webster, 2012).

3. History



To understand the fashion industry today, first a brief overview of how fashion industry emerged needs to be provided. Beginning with the prehistoric age (500.000 - 100.000 years ago), fashion didn't exist, as garments were used only for utility purposes such as keeping people protected and warm. They were manufactured from animal body parts and faunal elements, the techniques of putting them together including scraping, cutting, and piercing elements to get the desired results. The people's need to create these garments marked the beginning of modern civilization (Gilligan, 2018). The Neolithic era records the first breakthrough of the fashion industry, namely the discovery of woven fibers and the techniques of processing them to create better garments, such as weaving and spinning, techniques that were used until the invention of the sewing machine (Bellis, 2020) (Barber, 1993). The transition from garments to clothes, which can be interpreted as the beginning of fashion, was done in the ancient age, as the Roman, Greek and Egyptian empires began to use more complicated designs and colors to indicate their higher position in the society, which can be compared to what fashion means today (Tortora, 2013). Moving on to the Middle Ages, this was the period when the basics of a fashion industry was developed. By enhancing the loom to a horizontal one, which allowed for a more efficient cloth production, a domestic crafts system was put into place. Switching from individual cloth-making to clothiers, which were buildings in which production was centralized, the manufacturing processes were taken at a larger scale and an environment for fashion developments was put into place. (Medievalists,

2018) (Johnston, 2013). The most important era for the fashion industry was the industrial revolution (19th century), when the mechanical sewing was invented (International Sewing Machine Collectors Society, (n.d.)). This allowed for a shift in the speed of clothes making, as the innovative inventions were able to sew at impressive rates, of over 900 stitches per minute, enabling the ready-made clothing industry to take off (starternoise_admin, 2014). The 20th century marked the official beginning of the modern fashion industry, which was driven by the emergence of the consumerism culture and the lack of barriers of international trade, with innovations in the marketing and commerce sectors.

4. PRESENT

A. Present digital innovations

As previously mentioned, this paper focuses on three levels of digital innovation in the fashion supply chain: design, manufacturing and distribution. Each part has its own technological advancements that have disrupted traditional approaches and enhanced the processes involved in the supply chain.

In terms of **design**, one of the fundamental changes the fashion industry has encountered is represented by the computer technology **CAD (Computer-aided design)**. Through this innovation fashion designers can create geometric models for object shapes in real or virtual designing. The major benefit brought by this technology is that users can visualise designed fabrics on the computer screen using virtual models (Stylios et al., 1996). This way, they save time and efficientise the designing process, since fewer modifications will be made later on. Therefore, a CAD program includes different fabric preferences, textures, colours that are tested by designers before the actual garment fabrication (Fontana et al., 2005a, Fontana et al., 2005b).

Since CAD is used in initial stages of creation, **3D modelling** came as a complement that allows designers to render and visualise their work so that fashion items can be analysed from a more realistic perspective. By using 3D softwares, the information gap between fashion designers and manufacturers or customers is narrowed since the virtual clothing can be seen in a final form.

Another innovation which makes the process of visualisation more comprehensive is **AR (augmented reality)**, a technological advancement that has been growing constantly in recent years. AR is embedded in devices we use on a daily basis (such as smartphones and tablets), and that is one of the reasons for its success. Designers prefer to use AR because it is easy to implement and offers through digital effects an

authentic perspective of virtual fashion items. This innovation is generally used in the prototyping phase of the design process.

When it comes to the **manufacturing** stage, this part of the supply chain has also faced important technological innovations which changed the traditional way of production. **Automated systems** have become an indispensable segment of the new manufacturing processes. Through robotics technology and implicitly industry automation, the speed and accuracy of the production stage is more efficient, as the human intervention is minimised. Consequently, the automated systems have reduced human capital and conserved energy while enhancing productivity and the quality of the outputs. **3D printing** is another innovation through which different products are created. For instance, by using this innovation Nike decreased the time of prototyping and production of some lightweight plates used in football cleats from 2-3 years to around 6 months (Molitch-Hou, 2014). Other benefits of 3D printing are a decentralised production (at the point of sale), together with less packaging, transportation and storing (Atlantic Council, 2011; Huang, Liu, Mokasdar, & Hou, 2013).

While the Internet has become common nowadays, in fashion is still seen as innovation used mainly in “**smart factories**”. In an industry 4.0 setting, the Internet connects the automated systems with human interaction beneath a factory’s roof to create a networked, integrated ecosystem. Digital manufacturing processes represent a main part of such a system where smart products and smart networks are interrelated with smart factories under the new paradigm of fashion (Teunissen, José and Bertola, Paola, 2018).

The last part of the supply chain affected by technological advancements is the **distribution** stage. Here, **blockchain technology** plays an important part of how the fashion industry is evolving. With key characteristics like decentralization, immutability and consensus, blockchain technology has the potential to enhance the existing fashion industry by adding an extra layer of security and trust to it. For brand owners this innovation has come as a tool for having a clearer image regarding its products within the supply chain. They can check the position of their goods in the market at any time and therefore combat grey goods markets (Burstall & Clark, 2017). Typically, the supply chain in the fashion industry is long, complex and demanding in nature. The ecosystem of an apparel supply chain generally comprises of sourcing raw materials (fiber, yarn, fabric) from in-house or from outside vendors, manufacturing of apparels which can be again done in-house or through outside vendors, distribution of apparels through distributors and wholesalers and finally the apparel product reaches the retailers from their it reaches the customers. By using this blockchain, the speed of distribution is increased, since human interactions are limited. This innovation is

changing the fashion industry due to its traceability and sustainability of the record keeping systems regarding manufactured products (Wang et al., 2020).

Big Data and ML is used to efficientize the supply chain. Besides blockchain, predictive analytics came to disrupt traditional approaches in terms of trend forecasting and global distribution. Via the statistical method of predictive algorithms, historical data is used to predict future movements. It can be used in analysing future customer trends and purchases or identifying fraud. Any fashion brand can implement such a technology by outsourcing or using their internal system. **Predictive analytics** are developed firstly by collecting data, then cleaning irrelevant components such as outliers, spikes and anomalies (Luce, 2018). Once relevant data sets are formed, the next step is the visualisation, a process that could uncover trends before using machine learning or predictive algorithms.

B. Market Overview

As the fashion industry is in continuous change, it is beneficial to acknowledge the key drivers within it. According to Statista, the annual growth of the fashion industry averaged around 14.2% between 2017 and 2025, signaling the increased interest in the sector. Main drivers of this growth are represented by the expanded access to online commerce, the emergence of global markets besides the ones in the West and the increased income of the middle class population (Orendorff and Dopson, 2022). According to McKinsey's 2019 Report, China was responsible for almost 38% of the international fashion-industry growth, with a special focus on the luxury segment (Amed, Balchandani and Berg, 2022).

Some of the most important players in every stage of the supply chain can be identified in the following table. In terms of design, the main platforms used by fashion designers to conceptualise their clothes are Adobe Illustrator, Digital Fashion Pro and Corel Draw. When it comes to 3D fashion design, CLO Virtual Fashion represents a major competitor as well.

Regarding manufacturing processes, a large number of renowned fashion brands made the transition to "smart factories". The ones worth mentioning are Nike, Levis, or Hugo Boss. Even though the innovation of 3D printing was not implemented on a global scale, there are still some important companies which developed clothing items through this technology, including Julia Daviy, VOJD Studios and Julia Korner (P., 2022).

C. Drivers of digital innovations

The digital developments in the fashion industry that have shaped its current state were empowered by four main factors, namely the rise of sustainable global consciousness, the need of transparency, the emergent technological innovations, and the increased global consumption.

Sustainability plays an essential role (Innovation textiles, (n.d.)) in the tech development of fashion value chain, as more and more customers are aiming to use products from companies which adhere to green manufacturing processes and do not affect the environment. This meant that fast-fashion practices – unethical labor work, energy waste, water and air pollution - had to be reduced, which was achievable only by adopting innovative practices. Thus, more and more companies, from local creators to major conglomerates – Inditex (Inditex, 2016), LVMH (LVMH, (n.d.)), H&M – are shifting towards a circular business model, which ultimately reduces resources waste and optimizes the overall production processes. This can be achieved only by adopting eco-design practices and changing the manufacturing processes towards ones that satisfy the customers and matches their companies' identities.

Another relevant factor is the **emergence of technological innovations** that shape the modern economy. Industry 4.0 has allowed more market players to penetrate the sector, thus leading to an increased competitiveness, as tech fashion companies are taking over the industry (Analytics India Magazine, 2021). This has pushed the fashion value chain to rapidly adhere to the new trends and enhance their already current practices in order to be ahead of their competitors. From developing better algorithms for trend predictions (Silva, Hassani and Madsen, 2020), to using Artificial Intelligence (Oosthuizen *et al.*, 2021) and Machine Learning programs (Nagar *et al.*, 2021) to optimize operations and minimize costs, or switching to cutting-edge design innovations, the companies are trying to ensure that they are fostering an innovative environment that will provide them a place in the industry.

The **need for transparency** cannot only be attributed to the customers' desire to understand from where their clothes are coming from, but also from the retailers' demand to better control the overall value chain. As fashion is characterized by a high workforce and multiple design, manufacturing and distribution processes, it is becoming harder and harder to optimize the operations. Thus, the tendency to adopt radical digital innovations (Machado, 2014) – blockchain (Amed *et al.*, 2020), big data analytics, AI and ML - and mold them to the industry's needs cannot come as a surprise, but rather as necessary development in order to ensure their success.

Lastly, **increased customer demands** (Gazzola *et al.*, 2020) such as better textiles, personalized products, lower prices, and better shopping experiences have made the industry players to find innovative solutions that would reduce their costs while also creating unique products, fitted to each clients' personality. 3D printing (Wang *et al.*, 2011) and smart factories adaptations have been a result of this trend, and while still not at the level of mass personalization, it is clear that the industry's direction is towards that.

5. DIGITAL INNOVATION THEORY

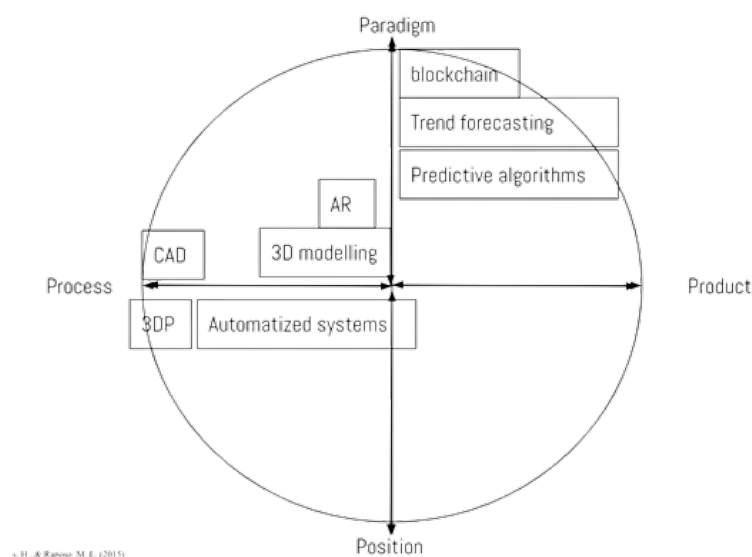
Digital innovations have transformed and shaped today's world in every possible aspect, from a social, entrepreneurial, and even politic point of view (Ciriello, Richter and Schwabe, 2018). Given the fact that digital innovations are ever-changing, it is increasingly harder to properly define them and categorize them into traditional frameworks that would help the business environment to adapt to them. However, over the years, numerous models have been developed, which try to classify digital innovations, such as the Henderson Clark model (Henderson and Clark, 1990), the SAMR model (Terada, 2020) or the 4P's model. While it is still difficult to perfectly adapt such frameworks to digital innovations, due to the rapid advancements that overcome the theoretical methods, it is extremely valuable to use them, as they provide an opportunity to understand their practical applications and the future development trajectories.

In the digital innovation theory era, there are multiple ways to characterize these technological advancements based on the source of their apparition, from demand pull to market push or even hybrid. A demand-pull innovation emerges as a result of market needs that are not met by the companies from a certain sector (Penpoin, 2019), and in the fashion industry, this is exactly the case. Retailers had to enhance their value chain practices in order to stay ahead of the new-entry competitors, appeal to the customers' modern needs (Pantano and Viassone, 2014), and adapt to the environmental policies. Further, a technology push innovation can be characterized by the availability of technologies in the market, which can be easily adapted to a sector to augment their services (Di Stefano, Gambardella and Verona, 2012). In the fashion industry, the high number of technological advancements such as 3D printing, blockchain or 3D modelling made it possible to effectively integrate these in the value chain processes and optimize them.

On top of that, as previously mentioned, a number of frameworks have been developed in order to better integrate the digital innovations advancements and understand their

effects on certain industries. A particularly interesting model is the 4P's (Francis and Bessant, 2005), which aims to improve a firm's operations by targeting it on four levels: Product innovations, Processes innovations, Positioning innovations and Paradigm innovations, all of which are classified by their incremental or radical identity in the company. If Product, Positioning and Processes levels refer to changes in the way products are created, to the way the merchandise is offered to the consumer and to the way existing methods are optimized or replaced, the Paradigm level refers to the impact digital innovations have in the underlying models of an organization. Also, an innovation can be classified as incremental if it brings improvements to already existing technologies, while a radical one completely changes the previous methods.

In the context of the fashion industry, this framework can be adapted, by replacing the company with the overall sector and analyzing the technological advancements by its implications on the four levels.



4P's model adapted to the fashion industry

By focusing on the fashion value chain, which does not focus on the way products are received and perceived by the customers, the digital innovations are only integrated on two levels, Process and Paradigm ones. To begin with, blockchain, trend forecasting, and predictive algorithms can all be categorized as radical paradigm innovations, as they have completely changed the way the industry is run and offered an opportunity to get ahead of their competitors. If blockchain allows the companies to get a personalized and exact overview of their product streamline processes, which was not possible before due to the immense dimensions of these firms, the trend

forecasting and predictive algorithms foster the possibility of appealing better to the customers than their competitors, through developing more efficient AI and ML models that capture data trends better. On the other side, there is no doubt that CAD software and 3D printing have completely shifted the design and production stages. Switching from manual design, namely pen and paper, to projecting them on virtual models, has optimized time efficiency. Moreover, 3DP is an invaluable asset that streamlined the prototyping process and allowed for producers to understand their products without wasting resources, by adjusting their mistakes before the production stage. While augmented reality and 3D modelling are radical innovation by their own, in the case of fashion industry value chain they can be defined as rather incremental innovations, as they add up to the existing digitally enhanced design processes. AR and 3D modelling facilitate the designers with improved methods of visualizations of the garments, by incorporating them to human bodies and seeing exactly how they fit to a person.

6. FUTURE DEVELOPMENTS

The fashion industry value chain has been extremely impacted by the digital innovations in the past decades, shifting completely the business models. The future holds promising outlooks and suggests more radical changes to the way clothes are created, produced, and distributed to the mass markets. The prospective digital innovations are spread on all of these levels, indicating a complete shift of the industry.

A. Material innovations

Novel fabrics have a high potential in redefining the way people perceive and wear clothes, as they could bring other types of functionalities than protection and social integration. The concept of wearables – wearable technology – is not new, especially in the past years with the apparition of smart watches, rings, or Google glasses. However, at this point, they are only gadgets that complement the other products, and are not seen as fashion items that could be used for other purposes.

One of these purposes specifically could be health monitoring, as most of these gadgets already hold all of the measurement functionalities, that could be used not only for sports athletes but also for people for which this type of information is crucial³. On top of that, innovation in terms of materials also include fabrics that will be able to change patterns and colors, by incorporating technological electronic innovations. This will change how people use clothes, allowing for higher flexibility and less waste, but

also impact how the production volumes of retailers, as consumers will not need any more as many products (CB Insights Research. (2021)).

These types of innovations are already starting to be put into place by researchers at MIT (MIT (n.d.)), who are creating 3D objects with “photochromic inks”, or Google (Google 2019), who is investigating how fabric can be programmed to change consumers’ moods, but there are still a lot of steps to be taken until it will reach customers.

B. Automated sewing machines

Although sewing machines can be classified as the first modern innovation in the fashion industry, little to no radical advancements have been made to this machine, due to the difficulty that fabric handling presents. However, in the past few years, more and more improvements have been brought to this scene, with gadgets such as the SewBot (Core77, nd), and more prototypes (Davis, n.d) are promising to resolve the fully automatization of garments production. This will be a total game-changer for the industry, reducing the human workforce and increase the production capabilities to 100%.

C. Mass customization

Customers’ needs have evolved over the years, focusing especially on personalization of the acquired products in order to make them unique and fitted to their preferences. Fast-fashion retailers will have to keep up with this trend, and they are investigating how they can uplift these processes to mass production. At the moment, only a few fashion companies offer this kind of possibilities, on products that are easier to manufacture. For example, Nike offers the opportunity to customize the sneakers according to one’s preferences, in terms of color changing. However, mass customization can be elevated to more products, through 3D printing and automated sewing systems, providing better clothes to the customers and increasing firms’ revenues.

D. Virtual and augmented reality

VR and AR are digital innovations that are already used in the fashion industry, but now they are only enhancing existing procedures. However, VR could completely disrupt the fashion value chain as it is known today, through the mass adoption of digital clothes. The implementation of the Metaverse to public consumers created the opportunity to shift from the physical universe to the virtual one, which facilitated a new type of market. Thus, virtual clothes could become the next big thing, and is already

becoming more and more popular, especially in the context of sustainability (says, 2020).

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