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# Exploring the nature of digital transformation in the fashion industry: opportunities for supply chains, business models, and sustainability-oriented innovations

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**ABSTRACT**

This article provides a comprehensive overview of the digital transformation of the fashion industry and describes the opportunities and influences on supply chains, business models, and sustainability-oriented innovations that it offers. Desk research was performed to review emerging cases of companies that engage actively in using 3-dimensional virtual and digital (3DVD) technologies, such as 3D modeling, virtual and augmented reality (VR and AR), 2- and 3-dimensional (2D/3D) scanning, and digital twinning (DT). The analysis shows how the adoption of digital technologies provides opportunities to dematerialize the traditional fashion supply-chain model of garment production and distribution and maps the innovative shifts occurring in the fashion industry's processes, products, and services. The adoption of 3DVD technologies by fashion companies unleashes new opportunities with respect to innovation in products/services and optimization of operational processes to streamline activities, shorten the lead time for designing, prototyping, manufacturing, marketing and retailing, and reorganizing the working phases. These capabilities also drive multicentred business-model innovations and thus affect value creation and delivery and capture changes. In addition, the analysis shows that digital transformation affects the four dimensions of sustainability that are interconnected intrinsically across supply-chain processes. Cultural sustainability is paramount, as fashion is a complex cultural system that is able to create products/services that influence the environment, economy, and society. In particular, 3DVD technologies promote cultural transformation of design processes to achieve a remix of skills and open knowledge, a behavioral shift from the consumer perspective in terms of diversity and self-expression, and a change in the organizational culture of companies that drive the digital transformation.

## Introduction

Researchers contend that the application of Industry 4.0 technologies in the fashion sector is bringing about transformative and disruptive changes in the back and front ends of the value chain and these alterations are resulting in more innovative (faster, more intelligent, and efficient) processes, products, services, and business models (BMs) (Bertola and Teunissen 2018; Kalbaska and Cantoni 2019). However, the application of digital technologies in the fashion industry has long remained in an exploratory stage due to a number of inhibitors and barriers that affect the pace of adoption (e.g., financial constraints, insufficient expertise, resistance to adoption) (Pal and Jayarathne 2022; Santos,

Montagna, and Neto 2020; Sassi et al. 2021). The COVID-19 pandemic has propelled a digital shift of the fashion industry toward the virtual dimension with a promise to enhance innovation and sustainability in all phases of the system (Brydges, Retamal, and Hanlon 2020; Gonzalo et al. 2020). Digital technologies are likely to have significant effects on the industry's future by providing opportunities to dematerialize resource-intensive practices in traditional fashion-supply chains and to co-create value in different sustainability dimensions (Business of Fashion and McKinsey & Company 2020).

Existing research has focused primarily on technological advancements that are required for widespread adoption (Papachristou and Bilalis 2015; Spahiu et al. 2021). However, the majority of these

studies have tended to overlook a comprehensive business perspective on the way digital technologies diffuse through current industry practices (Ibarra, Ganzarain, and Igartua 2018; Parida, Sjödin, and Reim 2019). In particular, only a limited number of systematic overviews to date have covered transformation in products and processes and BM innovations attributable to the digitalization of fashion systems throughout the value chain. In the literature on digital transformation of the fashion industry (with a specific focus on 3-dimensional (3D) digital technology), we identified only two studies that provide a comprehensive value-chain perspective (Arribas and Alfaro 2018; Noris et al. 2021). Moreover, empirical evidence of the influence of 3D digital fashion remains scant (Arribas and Alfaro 2018). In summary, the effects of digitalization on the sustainability of the fashion system represent an emerging topic of research and is one that currently lacks a holistic perspective because inadequate attention has been devoted to its cultural dimensions (Malin and Ryder 2018). This is a major limitation in light of the fact that fashion is one of the most culturally intensive industries (Bertola et al. 2016; Martin and Vacca 2018).

This article provides a comprehensive overview of the nature of digital transformation in the fashion industry, describes the influence of digital technologies on the fashion-supply chain, considers innovation in the digital business model, and focuses on the digital effect from a multidimensional perspective of sustainability. By conducting a systematic review of the grey literature, we derive empirical evidence from companies that engage actively in using digital technologies (e.g., 3D modeling, virtual and augmented reality (VR and AR), 2- and 3-dimensional (2 D/3D) scanning, and digital twinning (DT). Our data analysis focuses on the effects of digitalization on the fashion-supply chain in product design and development, business-to-consumer (B2C) marketing processes, retailing, and production phases. In addition, we map emerging shifts in BMs with respect to supply-chain processes, products, services, and value-architecture dimensions (e.g., value creation, delivery, and capture) that are occurring because of digitalization. Finally, we highlight the dematerialization and sustainability effects of adopting 3D virtual and digital (3DVD) technologies by taking a holistic approach that includes culture as a fourth dimension of the phenomenon in different phases of the supply chain. The overarching scope of the article is intended to support academics and practitioners as they navigate this novel, dynamic, and applied research field by discussing emerging limitations and sustainability challenges attributable to digital transformation in the fashion-supply chain.

## Literature review

### Overview of digital transformation of the fashion industry

Industrial digitalization involves structuring, shaping, and influencing transformation along different, albeit overlapping, dimensions – economic, societal, and cultural (Brennen and Kreiss 2016).[1] Enabled by digital technologies, digitalization and digitization of data and processes lead to digital transformation that is associated with altering value-creation paths and offering new products and services while managing the structural changes in, and the barriers to, the transformation process (Vial 2019).[2]

The digital transformation of the fashion industry affects the entire value chain in which radical changes occur in the relationships with customers and in supply-chain operations as a result of adopting 3DVD technology (Arribas and Alfaro 2018). The application of 3DVD technological systems that use computer-generated representations of a garment or accessory in the different stages of production and distribution influences customers' experiences and behaviors and offers opportunities for dematerialization of the fashion sector. Analysts have long defined dematerialization as reducing the amount of materials and energy used in the production and consumption phases of finished products and services (see, e.g., Wernick et al. 1996). Adopting 3DVD technologies in the fashion industry allows a nonphysical economy to emerge in which garments and services exist beyond the physical realm and contribute to dematerialization because they will never be produced in reality. Further, 3DVD technologies are associated with the digital transformation of several phases of the life cycle of fashion products and this allows some material activities to migrate to digital activities while enabling continuous information flow to improve product life-cycle management (Riedelsheimer, Dorfhuber, and Stark 2020; Brynjolfsson and McAfee 2014).

In the following sections, we present a detailed overview of the effects of 3DVD technologies on the fashion-supply chain, provide a design-driven perspective on the phenomenon, and describe digital BM innovations.

### The effect of digital technologies on the fashion-supply chain

A review of the existing literature shows that adopting 3DVD technologies leads to structural changes in the traditional supply-chain model of fashion companies. The use of 3D modeling allows the design and development workflow to be integrated,

optimized, and enhanced through complete digitalization and integrated processes of design and iterative prototyping, including tests of fit, simulation of functional performance (e.g., thermal), visualization of esthetic features (e.g., color, pattern, and material), and manufacturing specifications (Papachristou and Bilalis 2015). This digital approach optimizes material-resource consumption for physical sampling, shortens the time for production, fosters design creativity, and reduces costs (Demarco et al. 2020). The 3DVD technologies allow for made-to-measure algorithmic and computational design (Volino et al. 2005) that improves the way garments can be personalized and adapted to the needs and behaviors of users (Carulli et al. 2017). In the production stage, machinery that is able to read digital models allows operations to be streamlined; enhances precision, efficiency, and time; and optimizes resources to produce more complex and customized products (Paritala, Manchikatla, and Yarlagadda 2017). Digital production-on-demand permits lead time and logistics to be reduced through eco-efficient, localized, and on-demand small-scale, urban micro-factories that configure a shorter supply chain by eliminating the stock of unsold products and offering better working conditions (Clarke-Sather and Cobb 2019; Ashby 2016). Furthermore, 3DVD technologies have widespread applications in the final steps of the supply chain, particularly in the retailing stage that provides virtual fitting opportunities and reduces returns of items purchased online (Robertson et al. 2020). In addition to the mere physical ownership of goods through commercial transactions, digital retailing allows enhanced customer experiences by providing new services (e.g., personalization) and transporting people in imaginative, gamified, and immersive contexts (Silvestri 2020).

### Digital business-model innovation

Previous research has only to a limited degree investigated how digital technologies – specifically 3D, VR, and AR – influence BM innovation in the fashion industry (Arribas and Alfaro 2018; Bertola and Teunissen 2018; Noris et al. 2021). Building on Osterwalder and Pigneur's (2010) definition of BM, this article addresses this research gap by mapping changes in value creation, delivery, and capture that these digital technologies in fashion firms can trigger. The fundamental changes in these value dimensions attributable to digitalization are referred to as digital BM innovations. According to Osterwalder and Pigneur (2010, 14), "A business model describes the rationale of the way an organization creates, delivers and captures value." To further illustrate the firm's logic of doing business, these authors propose the BM canvas, a conceptual tool that consists of nine interconnected building blocks. In particular, value creation accounts for key activities, resources, and partnerships. Value delivery includes value propositions that are encompassed in product and service offerings, customer segments, relationships, distribution, communication, and sales channels, while value capture describes the financial implications of value creation and delivery (i.e., cost structure and revenue streams).

Among the existing studies that have investigated the effects of digital technologies on business logic, Ibarra, Ganzarain, and Igartua's (2018) literature review identified the shift to a service-oriented, network-based, and user-driven approach. Consistent with this strategy, innovative product-service offerings are co-created through extended stakeholder networks as the result of horizontal and vertical value-chain partnerships that are more aligned/responsive to users' needs (e.g., personalized and on-demand small batch production) (Arnold, Kiel, and Voigt 2016; Ehret and Wirtz 2017).

Usually, the extending and reshaping of the value proposition behind traditional product/service offerings is attributable to the digitalization of operational model/business functions and the use of digital interactive technologies in communication and marketing that lead to more effective customer satisfaction (Berman 2012; Colombi, Kim, and Wyatt 2018). Further, new digital products and services that can be produced at relatively low startup costs are emerging, the value of which is determined in the use phase (Remane et al. 2017).

Bharadwaj et al. (2013) and Remane et al. (2017) have referred further to the shift toward a service-oriented platform model that takes advantage of the business ecosystem to co-create and capture value. In particular, multi-sided platforms are becoming a popular digital business archetype that increases product/service value through network effects and generates platform revenues (Teece and Linden 2017). In addition to cost savings attributable to automation, resource efficiency, and improved decision making in the operational model, the shift from physical and digital product offerings unleashes new revenue streams (Dijkman et al. 2015). New pricing models emerge, such as dynamic pricing, subscriptions, and performance-based contracting (Ibarra, Ganzarain, and Igartua 2018).

### Multidimensional perspective on sustainability

This article applies a holistic definition of sustainability that accounts for the fourth – the cultural – pillar that was not envisioned in the Brundtland Report (WCED 1987). Given that fashion is

defined by two main components – the intangible values encapsulated in its cultural significance and imagination and the tangible values that consist of the physicality of materials, fabrics, and production processes – we assert that the four pillars (environmental, economic, social, and cultural) should be considered as intrinsically interconnected. In particular, cultural sustainability refers to preserving and cultivating creativity, knowledge, beauty, identity, diversity, heritage, and history. It contributes to positive social and economic outcomes via education and the protection of intangible and tangible heritage (UNESCO 2010; UCLG 2010; British Council 2020). In the realm of the digital transformation of the fashion industry, exploring the adoption of digital technologies is particularly relevant for understanding their effects on traditional processes and techniques, in which innovation is fostered based upon the synergistic use of cultural heritage and new collaborative practices are pioneered, such that the engagement of communities allows cultural capital to be preserved (Bertola et al. 2016; Martin and Vacca 2018; Twigger Holroyd 2018). Cultural sustainability can also produce a change in the organizational culture of the suppliers involved in the fashion-supply chain. All internal and external supply-chain actors need to adopt holistic, systematic, and durable sustainability practices that include shared multidimensional sustainability values, norms, and beliefs (Linnenluecke and Griffiths 2010) and lead them to change their attitudes as well (Lopez-Torres et al. 2019). This holistic change in cultural mindset is also significant from a consumer point of view: more than any other industry in the world, fashion consumerism is supported by cultural norms and motivated by perceived physical or psychological obsolescence (Assadourian 2010). The possession of garments nurtures fashion consumption and use intended to fulfill cultural aspirations, perceived personal happiness, social status, and success (Ekins 1991). Nowadays, consumption models are becoming more eco-oriented and consumers are making choices based on companies' ethical conduct and social responsibility and supporting environmentally friendly or green practices/products (Rinaldi 2019). However, even consumers who show great concern for environmental and social issues experience conflictual behavior between the desires to be fashionable and to reduce their consumption habits (Mandarić, Hunjet, and Vuković 2022). Therefore, a cultural shift in consumption behaviors and a change of mind-set at the industry and business level is required to achieve an effective sustainable change (Niinimäki et al. 2020).

## Methodology

### Research design

This study was conducted through desk research that entailed collecting, analyzing, and evaluating cases derived from the grey literature and comparing them through qualitative analysis. Our approach was intended to achieve a more comprehensive and profound understanding of how fashion companies use 3DVD technologies to transform business practices in their supply chain because this knowledge is lacking in the peer-reviewed academic literature. The grey literature sources in the review included corporate and third-party industry reports (e.g., from nongovernmental organizations (NGOs) and consultancies); news articles; interviews; videos and presentations; and websites of fashion companies and projects that use 3DVD technologies to virtualize products, services, and processes along the entire fashion-supply chain.

Previous researchers (Adams, Smart, and Huff 2017) have acknowledged the advantages of using the grey literature as knowledge artifacts in a novel field of inquiry and applied subjects on which scholarship is lacking. Moreover, the overarching rationale of this article is to inform practice, so a systematic review of the grey literature is an appropriate strategy to conduct such a research inquiry (Adams, Smart, and Huff 2017).

We focused our systematic collection of resources on mapping the existing practices of established and emerging companies engaged in the 3DVD fashion sector worldwide. The research was conducted between January and June 2021 through a twofold approach to data collection. On one hand, we analyzed the companies that use fashion-design software for 3D modeling by browsing the websites of the current leading software houses for digital fashion (i.e., CLO3D, Browzwear, and Optitex). Concurrently, we broadened the research with the most common search engines (i.e., Google and Google Scholar) using specific keywords in English (i.e., "digitalization," "phygital fashion," "digital fashion," "virtual fashion," "3D modeling," "rendering," "companies," "start-up," "designer," "agency," "supply chain") to obtain a comprehensive and updated pool of data. The 245 companies that we initially identified (31% in Asia, 30% in Europe, 17% in the United States, 14% in Turkey,[3] 5% in the UK, 2% in Canada, and 1% in Russia) were filtered according to the following preliminary eligibility criteria: public data available from different sources, English as the primary language, and fashion as the main field of application. This selective evaluation excluded the vast majority of the Asian cases because of language issues and data

availability. We further screened the resulting 89 firms to filter the cases with respect to national/international positioning (e.g., balance of origin and location on a global scale), national/international coverage (e.g., balance of companies' reach), explicit focus on 3DVD technologies (e.g., level of investment/interest in digital transformation), and coverage of 3DVD technologies along the supply chain. We analyzed the shortlisted sample of 36 companies based on the following criteria: year and place of founding; type of business; level of maturity (established/startups); company size (see Figures 1 and 2); specific type of technologies applied − 3D modeling, VR, AR, 2 D/3D scanning, and DT; type of digital transformation occurring throughout the supply chain (design and development, presentation business-to-business (B2B), marketing business-to-consumer (B2C), manufacturing, retailing) in processes and products innovation; and sustainability aspects (cultural, social, economic, environmental) associated with digital transformation (see Table 1).

This analysis also allowed us to identify opportunities for BM innovation, specifically in terms of changes in the value creation, delivery, and capture associated with the adoption of 3DVD technologies. We did not perform a detailed review of changes in each building block of the BM canvas (Osterwalder and Pigneur 2010) for this article as that would have required more detailed data not accessible directly in the grey literature. The purpose of BM analysis here is to pinpoint emerging, yet not exhaustive, opportunities for digital BM innovation in the fashion industry. Previous research along these lines in other industries has adopted a similar level of analysis and concentrated on changes in value creation, delivery, and capture (Ibarra, Ganzarain, and Igartua 2018). With respect to value capture, the data that we collected from the grey literature allow only for a general evaluation of the way revenue streams are enhanced, with some examples of novel revenue models.

Other limitations of the grey literature are its moderate credibility (Adams, Smart, and Huff 2017) and tendency to downplay any negative implications associated with digital transformation. The prevailing emergent and positive image attributable to marketing and commercial interests should be considered when evaluating the results of the grey-literature methodology. To account for these limitations, we refer to the literature review in the discussion section which critiques the potential drawbacks of adopting 3DVD technologies in the fashion-supply chain.
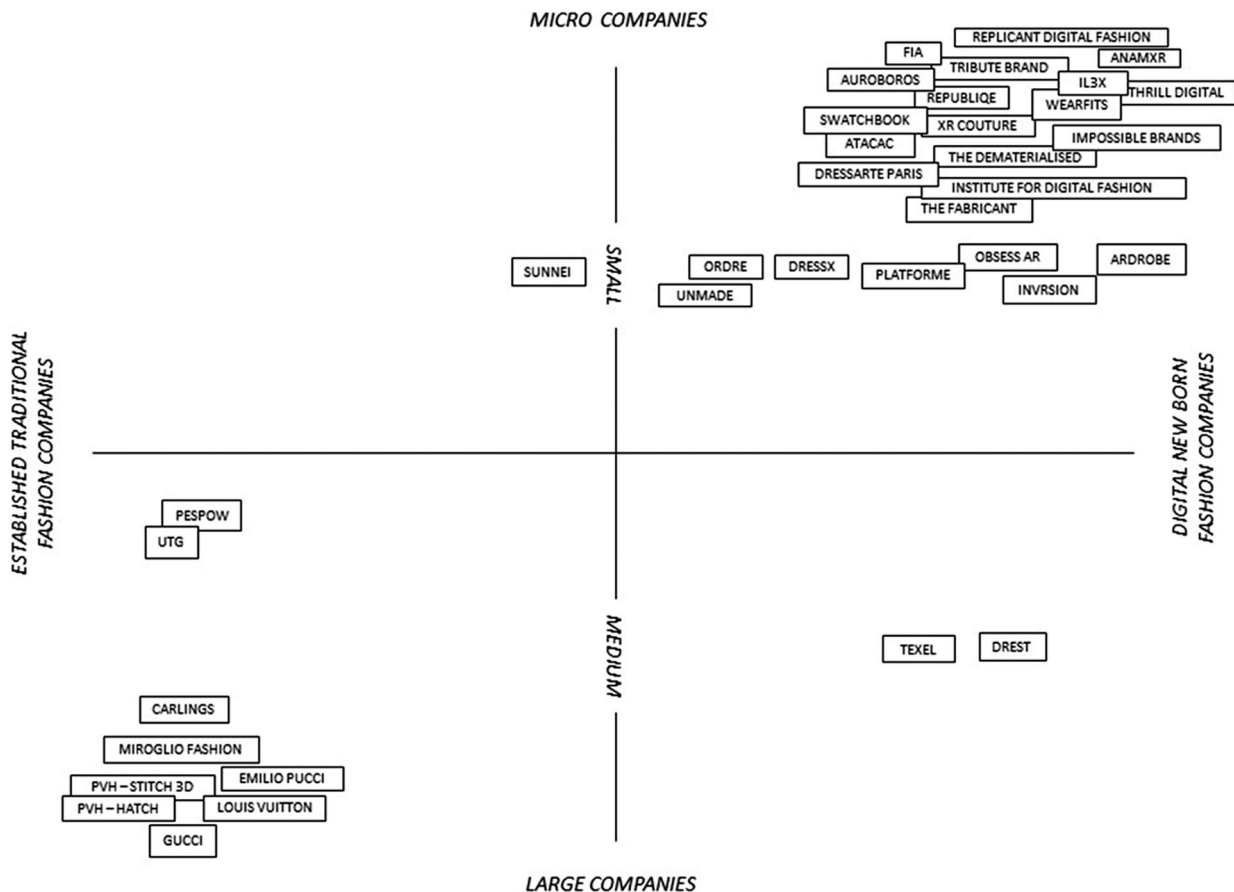


**Figure 1.** Taxonomy of selected cases mapping companies' dimensions (micro, small, medium, and large) vs. organizational typology (established traditional and digital new-born fashion companies).
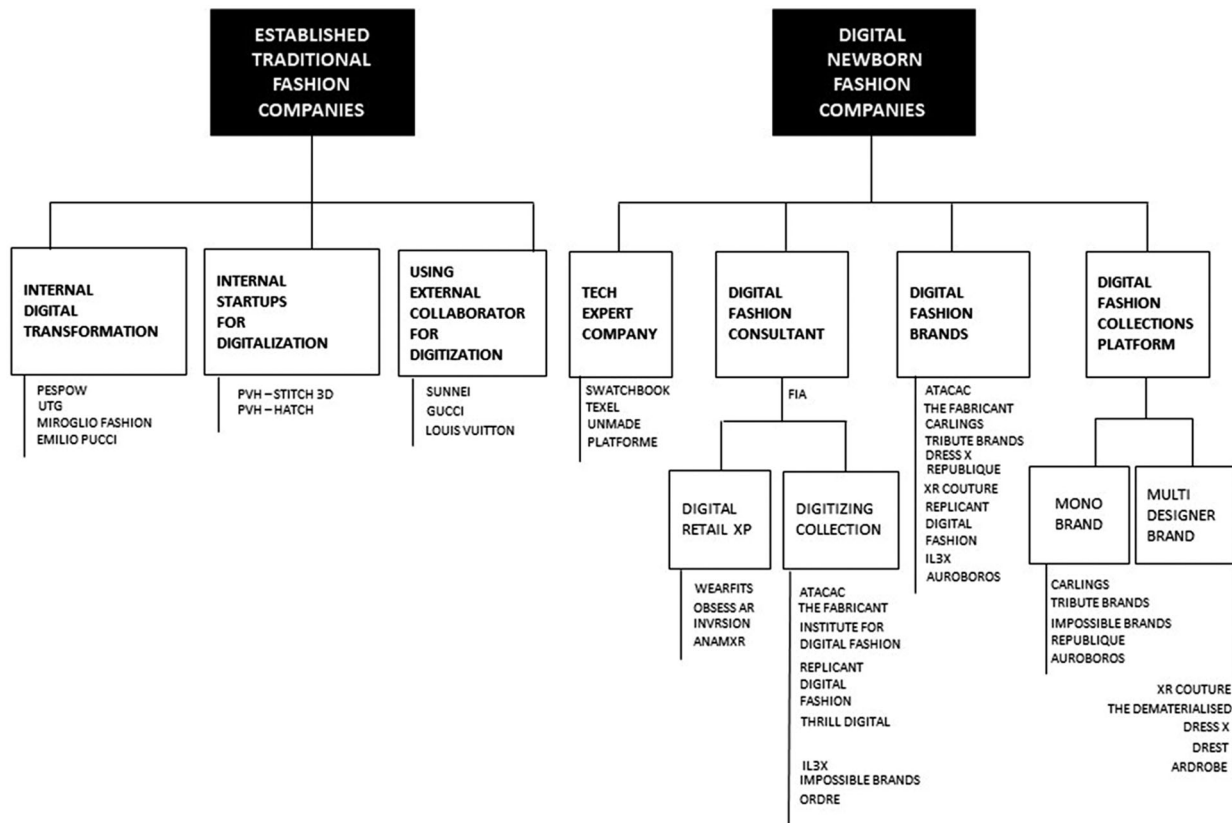
**Figure 2.** Taxonomy of cases that map companies' approaches to digital transformation through 3DVD.

## Results

### Company cases: analysis and taxonomy

The current situation is that 3DVD technologies are applied in two contexts: (1) established fashion companies and (2) innovative digitally-born startups/small- and medium-sized enterprises (SMEs), manufacturing, and e-commerce/retailing firms.

The first group approaches the digital transformation in three ways. First, they collaborate with external consultants to develop strategic partnerships with computer-generated imagery (CGI) expert agencies and digital fashion-design offices to digitize part of their business (e.g., Gucci, Louis Vuitton, Sunnei). Second, this group of firms incubates digitally-born startups (e.g., Hatch and Stitch 3D in PVH). Finally, they acquire internal competence (e.g., UTG, Emilio Pucci, Miroglio Fashion, Pespow).

The second group comprises micro and small digitally-born fashion companies that in the first instance exploit the maximum opportunities from 3DVD. Notable examples include digital fashion-consultant agencies that digitize collections (e.g., Atacac, The Fabricant, Ordre, FIA, Institute for Digital Fashion, Replicant Digital Fashion, Thrill Digital, Il3x) and support/create digital retail experiences (e.g., ObsessAR, Invrsion, Anamxr, Wearfits) or provide specialized technology-expert digitalization services (Swatchbook, Texel, Unmade, Platforme). Second, digital fashion brands operate their collections and also collaborate as consultants with traditional and established fashion companies (e.g., Atacac, The Fabricant, Replicant Digital, Il3x). Finally, digital fashion-collection marketplaces sell their own collections (e.g., Carlings, Republique, Impossible Brands, Auroboros, Tribute Brand) or host multiple brands as collective platforms (e.g., Dress X, XR Couture, The Dematerialized, Drest, ARdrobe).

In both groups of companies, 3DVD technology is applied in different phases of the supply chain to explore and exploit the new design and business opportunities of digital technologies, thus transforming the traditional fashion-supply chain either partially, (i.e., through limited digitalization of value-chain processes), or entirely, (i.e., through end-to-end digitalization of design, production, and selling of digital-only garments). With respect to supply-chain transformation that the application of 3DVD technologies allows, companies can be further divided into three clusters. Cluster 1 includes partial digitalization of the fashion-supply chain. Companies use 3DVD in production and distribution to generate virtual garments to support their traditional physical production and to run presentations and marketing in parallel to satisfy the interests of both distributors and retailers before they

**Table 1.** Thirty-six selected company cases classified by country, the companies' year of foundation or technological shift, level of maturity (established and digitally-born), company dimension, technology used, and fashion supply-chain transformation attributable to digitalization.

| # | Cases | Country | Year of foundation | Established traditional companies | | | Digital-born | | | | Company dimension | | | | Technology used | | | | | | | Fashion supply chain transformation | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Internal digital transformation | Internal startups for digital transformation | External collaborator/partnership for digital transformation | Digital fashion consultant | Digital fashion brands | Digital collection platform | Technology expert companies | Micro | Small | Medium | Large | 3D | AR | VR | 2D scanning | 3D Scanning | Digital on-demand production | AI | Design and development | Presentation marketing B2B | B2C | Manufacturing | Retailing |
| 1 | Atacac | Sweden | 2016 | | | | X | | | | X | | | | X | X | X | X | | | | X | X | X | X | X |
| 2 | The Fabricant | The Netherlands | 2018 | | | | X | | | | | X | | | X | X | X | | | | | X | X | X | | X |
| 3 | Carlings | Sweden | 2018 | | | | | X | X | | | | | X | X | X | | | | | | X | | X | | X |
| 4 | Tribute Brand | Croatia | 2020 | | | | | X | X | | X | | | | X | X | | | | | | X | | X | X | X |
| 5 | Dress X | USA | 2019 | | | | | X | X | | | X | | | X | | | | | | | | | | X | X |
| 6 | Sunnei | Italy | 2020 | | | X | | | | | | X | | | X | X | X | | | | | X | | | X | |
| 7 | Republiqe | Singapore | 2019 | | | | | X | X | | X | | | | X | | | | | | | X | X | X | X | X |
| 8 | XR Couture | India | 2020 | | | | | X | X | | X | | | | X | | | | | | | | | | X | X |
| 9 | The Dematerialized | UK | 2020 | | | | | | X | | X | | | | X | | | | | | | | | | | X |
| 10 | Drest | UK | 2019 | | | | | | X | | | X | | | X | | | | | | | X | | X | | X |
| 11 | Orde | UK | 2014 | | | | | | | | | | X | | X | X | X | | | | | X | X | X | | X |
| 12 | FIA | UK | 2013 | | | | X | | | | X | | | | X | X | | | | | | X | | | | |
| 13 | Institute for Digital Fashion | UK | 2020 | | | | X | | | | X | | | | X | X | | | | | | X | | X | | X |
| 14 | Replicant Digital Fashion | Russia | 2020 | | | | X | X | | | X | | | | X | X | | | | | | X | | X | | X |
| 15 | Thrill Digital – Thrill XR | UK | 2020 | | | | X | | | | X | | | | X | X | X | | | | | X | X | X | | X |
| 16 | Wearfits | Poland | 2019 | | | | X | | | | X | | | | X | X | X | | | | | X | X | X | | X |
| 17 | II3x | Italy | 2020 | | | | X | X | | | X | | | | X | | | | | | | X | | | | |
| 18 | Impossible Brands | Italy | 2020 | | | | | X | X | | X | | | | X | | | | | | | X | X | X | X | X |
| 19 | ARdrobe | Italy | 2021 | | | | | | X | | X | | | | | X | X | | | | | | | | | X |
| 20 | Obsess AR | USA | 2017 | | | | X | | | | | X | | | X | X | X | | | | | | | | | X |
| 21 | Invrsion | Italy | 2015 | | | | X | | | | | X | | | X | X | X | | | | | | | | | X |
| 22 | Anamxr | USA | 2020 | | | | X | | | | X | | | | X | | | | | | | | | | | X |
| 23 | PVH – Stitch 3D | The Netherlands | 2018 | X | X | | | | | | | X | | | X | | | | | | | X | X | | X | |
| 24 | PVH – Hatch | The Netherlands | 2017 | X | X | | | | | | | X | | | X | | | | | | | | | | | |
| 25 | Pespow | Italy | 2016 | | | | | | | | | | X | | X | | | | | | | X | | | X | |
| 26 | United Textile Group (UTG) | Denmark | 1968 | | | | | | | | | | X | | X | | | | | | | X | | | | |
| 27 | Auroboros | UK | 2018 | | | | | X | | | X | | | | X | | | | | | | X | | | X | X |
| 28 | Gucci App-Ace Sneakers | ITALY | 2019 | | | X | | | | X | | X | | | | X | | | | | | | | X | | X |
| 29 | Louis Vuitton | Italy | 2020 | | | X | | | | X | | X | | | X | | X | | | | | X | X | | | X |
| 30 | Swatchbook | USA | 2017 | | | | | | | X | | X | | | | | | X | | | | | | X | | X |
| 31 | Texel | Russia | 2014 | | | | | | | X | | X | | | | | | | X | | X | | | | | X |
| 32 | Miroglio Fashion | Italy | 2018 | X | | | | | | | | | | X | X | | | | | | | X | X | | X | X |
| 33 | Emilio Pucci | Italy | 1947 | X | | | | | | | | | | X | X | | | | | | | X | X | | | X |
| 34 | Unmade | UK | 2013 | | | | | | | X | X | | | | X | | | | | X | | X | | | X | X |
| 35 | Platforme | Portugal | 2016 | | | | | | | X | X | | | | X | | | | | X | | X | | | X | X |
| 36 | Dressarte Paris | France | 2018 | | | | | X | | | X | | | | X | | | | | X | | X | | X | X | X |

move into production (e.g., PVH, Pespow, UTG, Gucci, Miroglio Fashion, Emilio Pucci). Cluster 2 entails full digitalization of the supply chain with virtual and physical garments. Companies implement virtual products and digital processes to support on-demand physical production. Virtual garments are used for presentations as well as trade and marketing activities to reach distributors/ retailers and final users to customize and calibrate the production (e.g., Atacac, Impossible Brands, Sunnei, Dressarte Paris). Cluster 3 involves full digitalization of the supply chain with virtual-only garments. Companies deliver these products through digital processes and services that allow nonphysical economies. They reach customers directly which allows digital distribution, customization, and consumption (e.g., The Fabricant, Replicant Digital Fashion, Republiqe) (Figures 1 and 2).

## Influence of digitalization on the fashion-supply chain

### Digitalization of product design and development

As considered in this study, the traditional fashion-supply chain is a structured process of sequential phases that embraces several steps: (1) research on market trends and fabric availability; (2) creative and technical design of new collections from style sketches to 2D drawings; (3) product-development analysis; (4) prototyping/making samples of the new models; (5) presentation/trade B2B; (6) manufacturing and assembly of garments known as cut-make-trim (CMT); (7) marketing garments by matching retail outlets to the new collections to achieve the broadest possible market access; (8) distribution through sophisticated logistics operations, and (9) retailing/selling garments to consumers through various retail channels. Even if represented linearly, the final samples that emerge from Step 4 are realized typically through iterative cycles of sampling/ alteration/design (Steps 2, 3, and 4). In this process, the 3DVD technologies change both the design workflow and product output dramatically as described below.

### Streamlined and faster workflow. Design and prototyping become a unique digital process that integrates pattern-making, fitting, and testing into the same virtual space for shortened cycles of iterations: Virtual samples can be ready within hours rather than days or weeks. This workflow also reduces/ eliminates physical sampling, manual work, and fabric use as a single refined physical sample can be prototyped at the end of many virtual interactions.

### Cross-department professional collaboration through enhanced communication. 3DVD is introduced more easily in the pattern-making and styling department. However, more creative and streamlined processes derive from a cross-use of digital tools among these departments, which allows for enhanced communication among stylists, designers, and pattern makers. Thanks to a more accurate representation of garments, closer cross-disciplinary collaborations of hybrid teams are enhanced compared to traditionally siloed design strategies, and allow rapid and simultaneous small iterations to achieve faster and shared local/global decisions. The virtual prototype gives designers a more detailed visualization of their initial ideas to control more effectively such functional and esthetic features as the three-dimensional shape of garments (volumes, length, details), the material variations, and the graphic positioning. It is also a faster way to express and exchange ideas with pattern makers who find real-time 3D model visualization an easy way to manipulate, correct, and perfect patterns.

### Enhancing creativity and providing more informed design and research expertise. 3DVD provides designers with greater creative freedom and a broader space of expressiveness. Virtual-only products (Cluster 3) may be made of unreal materials with no physically-based features but virtual-only behaviors (e.g., fire flames, liquid silver). Digital to physical products (Clusters 1 and 3) need the correct digital twin of the physical materials to create the best photorealistic simulations of the 3D digital garments. Digital agencies such as Swatchbook provide services to create high-resolution scanned images and metadata to create a digital replica of textiles. 3DVD design is also used as an exploratory tool for new design methodologies. For instance, Lindqvist (2015) from Atacac prototypes his kinetic garment construction in 3D as an innovative pattern-design approach based upon crucial biomechanical points tested on digital bodies (avatars). His digital prototyping allows to check better garment fitting and to match natural human movements. Furthermore, McQuillan (2020) uses 3D software to demonstrate that it can facilitate hybrid design and prototyping to achieve zero-waste fashion design.

### Sharing knowledge for its widest adoption in collaborative open-source communities. Digital fashion agencies and mono/multi-brand digital platforms build collaborative communities of experts with different digital competencies (i.e., designers, stylists, fashion bloggers, artists, and 3D, VR, and AR technicians/creators) proactively. This approach helps identify new talents in 3DVD design to speed

and spread the knowledge of 3DVD technologies in fashion and to efficiently advance an open-source fashion-design attitude.

*Digitalization of B2B presentation and trade.* 3DVD technologies are used primarily to visualize merchandizing for presentations and trade (both wholesale buyers and retailers) from the simple digitization of communication tools (i.e., digital lookbook, line sheet, and collection catalogues), to the digital transformation of fashion shows, exhibition events, and interactive digital showrooms, to the creation of advanced virtual hyper-sensorial narrative experiences.

*Enhancing communication.* Digital garments populate online virtual and dynamic platforms, including digital portfolios, enhanced digital assets, and wholesale pricing specifications. In addition, platforms allow interactive meetings and better visualization of all of the possibilities and collection variations of stock-keeping units (SKUs).

*Enhancing digital presentation: realism, interaction, and value experience.* To recover the loss of tangibility of garments, the best visualization of a collection shows the construction by mimicking every detail (e.g., fabrics, textures, patterns, fastenings, prints) precisely with 360° view images and videos with super-zoom capabilities to reveal the expertise and know-how of the brand. Further, dedicated immersive virtual environments allow spectacular fashion experiences (showcases, runways, and presentations) to be created that transport people in imaginative and immersive contexts, and thus limit travel, but enhance the narrative and perceived value of the collection. Further, visual experiences may be enhanced through sonic and haptic technologies in VR/AR to stimulate sensory perceptions in the digital realm.

*Enhancing the one-to-one relationship between brands and buyers.* Interestingly, digitally-driven wholesale activities can track and archive the interactions between brands and buyers. The resulting data analytics and metrics can provide insights for developing customized and collaborative digital collections and managing the global wholesale network for successive on-demand production (Cluster 2). For example, the Sunnei Canvas digital platform permits selected buyers to intervene in the design aspects of each collection item (i.e., shape, fit, materials, colors, dyeing, stitching) to differentiate their assortment and customize exclusive products for each stakeholder. To enhance the one-to-one relationship with buyers, the company can base

production on their intentions, cut costs, and limit the wasteful sampling process.

*Digitalization of B2C marketing processes*
At their best, digital images are exploited to create contents for static, dynamic, and interactive audio/visual commercials for marketing campaigns. Digitally-based marketing is designed to attract customers in both partial and complete digitalization of fashion systems, particularly in the new workflow of "virtual to consumer" in which the intermediaries (buyers, distributors, retailers) are eliminated and brands communicate directly to the final user with tools similar to those described for the B2B presentations and trade.

*Digitization of retailing*
3DVD technologies affect new digital retailing experiences on e-commerce that allow users to be clothed digitally with images for their virtual use on social media (Cluster 3) and also to support more automated buying experiences, such as digital try-on and customization (Cluster 2).

*Digital try-on and customization.* Computer visioning and machine algorithms for automated 3D body scanning, measurement, and reconstruction help retailers (e-commerce or physical stores) provide digital try-on of virtual garments with a highly personalized fit, visualization of comfort, and size recommendations that reduce returns. VR technologies allow consumers to walk around a 3D store and to try on and purchase clothes through virtually-based experiences that require tangible tools such as a VR headset and touch controller. Further, the use of product configurators, including UnmadeOS and Platforme, allow products to be customized to provide consumers with self-expression and to allow them to manipulate data variables supported by the visualization system which delivers photographic renderings of the customer's unique design before it is made (Cluster 2) or never made (Cluster 3).

*Immersive retailing experiences.* Digital physical retailing allows consumers to engage in real-time, reliable, seamless phygital experiences of purchasing digital garments and seeing themselves dressed in them through a smartphone via camera access for AR (Clometrica/Replicant Digital Fashion, ARdrobe). Although this technology is in its infancy, it allows multiple and durable uses by creating an AR digital personal wardrobe (MyARdrobe) and uploading different digital contents for a physical garment that is purchased (The Last Statement T-Shirt, Carlings).

### Digitization of production

The application of 3DVD technologies allows for optimization of traditional production processes, digital made-to-measure, and production-on-demand approaches that are sometimes supplemented by locally-based micro-factory production. A firm's business strategy influences the way 3DVD technologies transform its production processes. Using 3DVD technologies to optimize the physical production process alone is more common on the part of companies that started as traditional fashion brands and for which physical garments form the basis of the value proposition (Cluster 1). In contrast, digital made-to-measure and production-on-demand is an approach common among small, digitally-oriented fashion firms that focus on selective, unique, and customized digital (Cluster 3) and digital/physical garments in their product portfolio (Cluster 2).

**Optimization of traditional/physical production processes.** 3DVD technologies allow for more informed decision making and collaborative planning and thus lead to faster and more resource-efficient production cycles. Companies in Cluster 1 use 3DVD in the backend to generate virtual garments to help optimize traditional physical production.

**Digital made-to-measure approach.** Digital garments used as virtual filters superimposed onto the digital identities of users (static images or videos) on social media are manipulated on demand (Cluster 3) with a made-to-measure approach. Digital tailors that manipulate digital clothes to fit the client's body image precisely mediate the process of digital dressing. For example, Dressarte Paris (Cluster 2) uses 3DVD in its made-to-measure custom tailoring services through accurate digital virtual measurements of a customer's body shape and offers a digital preview of personalized garments on a customized avatar.

**Production-on-demand using virtual products first.** The information collected during presentations and marketing campaigns, the data derived by tracking the use of virtual products in social media, and the preorder mechanism serve to determine the strategy of production-on-demand in Cluster 2. Products are not static entities, but dynamically configurable systems in which users can customize the variables based on their virtual representation. Technological platforms such as Unmade and Platforme allow technical digital files to be sent to factories automatically and tracked throughout the production stages.

In some instances, locally-based manufacturing activities supplement the digital production-on-demand that 3DVD technologies offer with a corporate strategy to further enhance the supply-chain craftsmanship, quality, speed, and flexibility. As a result, on-demand garments are developed with short production cycles (less than a week) which allow customer-driven services and environmentally-friendly trusted materials in niche market sectors (Atacac, Impossible Brands, Dressarte Paris). In addition to corporate strategy to enhance economic, environmental, social, and cultural value creation, the opportunity to implement consumer-driven local production depends upon the regional capacities available – for instance the ability to manage highly complex experimental processes and to access digital manufacturing laboratories (e.g., Atacac).

### Digital business-model innovation

The analysis in this section is based on mapping the changes in value creation, delivery, and capture based upon Osterwalder and Pigneur's (2010) definition of BM.

#### Changes in value creation
**Enhanced creativity, operational excellence, speed, and cost efficiency in design and production.** 3DVD approaches improve the value creation process of physical and digital product offerings in established fashion firms and digitally-born startups. These improvements include enhancing creativity and flexibility to meet the needs of clients, shortening new product development (NPD) times, automating, and achieving cost efficiency and operational excellence in design and manufacturing processes.

**Opportunities for open-source innovation and crowdsourcing.** Open-source fashion (giving Atacac and The Fabricant 3D files to download and use for free) and the organization of crowdsourcing events (The Fabricant's STEM event) can be viewed as value-creation approaches that facilitate digital fashion innovation by developing digital capabilities, networking, and increasing the community/network of 3D designers.

**Value co-creation in the business network/ecosystem.** Virtualization allows fashion businesses to offer cloud platform-based services, thus enabling opportunities to transform their business model (Hatch, Stitch 3 D, Sunnei, ARdrobe). These BMs facilitate value co-creation by managing transactional relationships/interfaces with other actors in the business network and unlocking opportunities for on-demand, customized, and personalized fashion offerings (both digital and physical garments).

***Ability to create economic, environmental, societal, and cultural benefits simultaneously.*** Many firms refer to advancements in the sustainability of the value-creation process as a result of digital transformation. These improvements are based upon operational/resource efficiency improvements, on-demand production, and personalized/customized clothing, which leads to the production of fewer physical garments that are used longer (Atacac). Further, digital fashion offers opportunities to completely dematerialize the traditional physical value-chain infrastructure.

Open-source innovation and crowdsourcing are approaches that benefit individual digital artisans by helping them to develop talent and providing access to the rapidly-developing digital fashion business (Atacac, The Fabricant). As an example, IL3X intentionally created the ARdrobe, a digital marketplace for AR fashion designers to showcase their talent and creations (IL3X). In contrast, Atacac also takes advantage of the opportunities offered by the blockchain marketplace that uses cryptocurrency to include creative artisans from various cultural and geographical contexts who do not have access to traditional economies.

### Changes in value delivery
***Virtualization of B2C BM content: digital garments and services as new product offerings.*** Virtualization of product content – the shift from analogue to digital fashion – makes it possible to create new digital products and services that can be viewed as a disruptive innovation to traditional fashion BMs. Largely, startups exploit this BM innovation based on digital B2C offerings, but traditional firms have begun to follow this development as well by offering virtual collections that complement physical garments, thus diversifying their product portfolio.

Digital pieces are created to wear on social media (e.g., The Fabricant, Carlings, Tribute Brand, Atacac, Republique, Gucci) or in games (AR/VR skins or filters by Tribute Brands, Louis Vuitton, The Fabricant). The latter represents a shift to adjacent industries to reach new market segments that fashion brands have not targeted traditionally. Offering purely digital pieces is complemented by providing cyber-tailoring services to help consumers fit the digital clothes that they purchase on their avatars.

The value proposition of B2C digital offerings is packaged differently. Some brands (Atacac, The Fabricant) promote uniqueness by releasing limited one-of-a kind digital pieces with embedded cryptoart (generative art generated from a single algorithm/code that can create one-of-a kind digital products) and nonfungible tokens (NFTs) based on the use of blockchain to prove the authenticity of garments. Using auctions to sell these pieces in a blockchain-enabled marketplace further enhances the exclusivity of owning these digital garments. Other brands, such as Gucci, frame their value proposition around affordability and accessibility to otherwise expensive luxury pieces. Many companies (e.g., Republiqe, Atacac, The Fabricant) articulate the sustainability benefits of digital clothes as part of their value proposition, namely by using fewer resources and addressing the wasteful consumption mentality.

***Virtualization of B2B BM content: digital platform-based services.*** Virtualization of collections that 3D and VR/AR technologies offer is the basis for BM innovations associated with the provision of digital B2B platform-based services designed to digitalize parts of the fashion-value chain (Hatch and Stitch 3D startups spin-offs of PVH, and Sunnei's Canvas). In particular, Stitch 3D allows fashion brands to develop capabilities in 3D product creation that foster creativity, allow a faster process, and reduce waste in the design and product-development phases. The Hatch digital showroom solution helps reinvent the essence of the wholesale experience beyond digital collection presentation. Various customization services are built in to adjust quickly to retailers' demands and to make decisions about collections easier without depending upon samples. The collection's marketing is improved as well through attractive presentation and storytelling. Waste reduction, enhanced operational efficiency, speed to market, and improved B2B relationship management are among the delivered business benefits that form the value proposition. Stitch 3D and Hatch software provide fashion brands with better insights into their digital strategy with digital transformation services based on cloud analytics. It is worth noting that Stitch 3D appeared after Hatch which allowed digital creation and rendering for the showroom, and thus made the digital service offerings complementary.

An idea similar to Hatch's digital showroom is incorporated into a Sunnei Canvas, a five-step customization program based upon a VR-enhanced platform that offers retailers services to co-create personalized and co-branded collections (e.g., change the type of fabrics, colors, length of sleeves on shirts, dyeing, and stitching details).

***Extension of value proposition in physical B2C product offerings.*** While the use of 3D and VR/AR in physical design and production of garments does not result in radically new B2C product offerings, it

still allows the value proposition to be extended compared to physical garments manufactured in traditional ways. For instance, kinetic garment construction results in clothes that are more comfortable/fit better, while 3D design and printing allow on-demand production and mass customization of individual physical garments (Atacac). Using AR/VR filters to augment physical garments improves customer engagement via user-experience gamification.

## Changes in value capture

With respect to the way digitalization affects the revenue streams and drives the profitability of the organizations that were reviewed as part of this analysis, we derived the following key insights:

1. Cost savings in the value-creation process of physical/digital garments derive from increased efficiency in operations/productivity and dematerialization. In particular, virtualization of design and prototyping leads to faster workflow and less material usage due to sample reduction/elimination and improved collaborative planning process across different departments or parts of the value chain (e.g., brands and retailers/distributors as in case of Sunnei Canvas). 3DVD technologies used in retailing and marketing (e.g., digital try-on with customization features) allow for accuracy in production cycles leading to fewer returns.

2. Product-differentiation strategies are enabled by improved customer-value propositions and better customer experience and engagement. For instance, digitalization allows the value proposition of physical clothes to be extended by shifting the focus from the product to the service/experience (e.g., gamification of user experience based on AR/VR, personalization, on-demand, and mass-customization services). This shift to service and experience orientations allows brands to pursue a differentiation strategy, thus enhancing the competitive advantage and profitability of firms.

3. Fashion companies launch new digital products and services in new markets/adjacent industries. The cases that we reviewed indicated that digitalization allows companies to diversify their product and market portfolio (e.g., Louis Vuitton provides physical and digital products such as AR/VR skins to wear in videogames and thus enters the entertainment market.

4. The launch of service-oriented platforms entails smaller amounts of capital investment and enables value co-creation with other actors in the business network, as demonstrated by the cases

of digitally-born B2B and B2C startups (e.g., Stitch, Hatch, The Dematerialized, ARdrobe).

Specific examples of new revenue streams include software-licensing models predicated on cloud-based subscription-software licensing (Stitch 3D and Hatch), digital sales of virtual clothes in blockchain-powered marketplaces using cryptocurrency and NFCs to authenticate transactions (Stitch 3D and Hatch), and royalties from the fee charged to orchestrate digital fashion-collection platforms (The Dematerialized). Other more common revenue streams include online sales of digital clothes and revenues from consulting services to support the digital transformaton of fashion. To enable the 3D-manufactured garments to be priced competitively, Atacac applies dynamic pricing based upon the pre-order model.

## Sustainability effects

### Sustainability in the design and development stage

A comparative life cycle assessment of environmental sustainability illustrates the positive effects of digital fashion sampling over physical sampling during the design and development phases. For example, Xiong (2020) found a considerable reduction in carbon footprint of up to 30%. Another study from Dressx (2020) compared the effects of creating a digital garment and e-mailing files to the clients to producing a physical garment. Creating garments digitally was found to reduce carbon-dioxide ($CO_2$) emissions by 97% and save 3,300 liters of water. However, neither study was complete, as they compared only simple garments, such as a tee-shirt that does not represent the average digitally-designed garment. Moreover, the studies did not describe the way digital garments are archived in the cloud, sold, and bought. These are considered energy-intensive processes that need to be included in the calculation of the environmental effects. Eliminating physical sample production completely (Cluster 3) and reducing sample production to only a few garments in the product-development process (Clusters 1 and 2) increase both environmental and economic sustainability. Iterating the design and prototyping activities digitally facilitates the product's development and achieves shorter cycles that hasten the time to market, cutting both costs and material waste. In addition, 3D modeling has been found to simplify the zero-waste design approach by making sustainability-motivated decisions in the early stages of the creative process and limiting the amount of textile waste in the design phase (McQuillan 2020).

The gender-neutral inclusive design approach that many of the emerging digital design companies (Cluster 3) are taking reflects the urgent need to remove from garments the social norms that inhibit the freedom of individuals. 3DVD technologies support cultural and social sustainability because of the opportunities they create for customization. The design of digital garments allows a more inclusive and democratic approach to the fashion industry's beauty standards, because, theoretically, each product can be personalized and fit to any body shape without traditional sizing constraints.

3DVD processes of design and development influence the design culture and methodology and facilitate a collaborative approach that helps to forge a community of people who work with 3D-fashion design tools to disseminate application of the technology in the sector (e.g., Atacac, Institute of Digital Fashion, The Fabricant). Team diversity is encouraged and supported to develop hybrid workforces that can bring different perspectives and expertise to fashion to achieve technological, cultural, and social innovation and sustainability. 3DVD technologies foster a cultural transformation in the design process and allow the exchange between established workers trained in updated skills and new professionals with enhanced expertise, thus altering traditional workflows based upon handcraftsmanship and material artifacts. The new design processes allowed by 3DVD technologies require a shared glossary and capacity to translate the material experience and the artisanal processes in a virtual modality to reach the same quality and attention to detail as that of the physical design.

### Sustainability in the B2B presentation and trade and B2C marketing stages

The digitalization of wholesale and marketing tools contributes to reducing/eliminating physical sampling and fabric and waste from prototyping processes, thus limiting their adverse environmental effects and increasing cost efficiency in the time to market. Decreasing yearly worldwide travel and transportation of collections associated to B2B wholesale during international fashion weeks over the four major fashion seasons has been found to reduce carbon footprint (241,000 tons of $CO_2$) and financial costs (Carbon Trust and Ordre 2020). By contrast, HFW with Normative (2020) calculated the environmental effects of the first completely digital fashion week held in Helsinki in the Fall-Winter 2020 season. It was found that the overall carbon footprint – calculated following the Greenhouse Gas Protocol (GHGP) – was higher than that of traditional fashion shows, but lower if calculated per visitor.

Digital B2B trading allows different stakeholders (buyers, retailers, and customers) to participate actively in altering/personalizing a collection without using physical materials and samples prior to the manufacturing process. In addition, online selection and management of B2B orders allow companies to accumulate data, simplify logistics, and structure their economic strategies based on interactions, decisions, and customizations of digital buyers.

From the cultural perspective, 3DVD technologies drive a cultural transition to value experiences rather than solely presenting and selling products. Depending upon the medium chosen, 3DVD technologies enable designers to regulate the expressiveness of virtual products/collections, increasing both realism and sensorial content. Fashion shows and marketing campaigns are designed through VR and AR to enhance and expand storytelling capacity of brands in terms of meanings and values to engage users and recover the loss of information and interaction that occurs when products/collections are presented to buyers digitally (e.g., material touch and face-to-face exclusive trading sessions) in comparison to physical trades.

### Sustainability in the retailing stage

The digital transformation of the retailing stage (Cluster 3) leads to new consumption behaviors linked to social media through an ethical reconsideration of the effects of fast fashion consumption and this can give consumers greater awareness of sustainability issues. The new interaction with clothing through digital purchases leads to environmental sustainability while it simultaneously takes into account the sociocultural aspects (Collins 2019): it fulfills fashion's social functions, such as self-expression, identity statement, and communication via social media, and reduces the size of the industry's carbon footprint as well as eliminates the buy once-dress/waste cycles in real life (Cluster 3). Nonetheless, a drawback is the replication of fast consumption behaviors in the digital realm.

Some attempts to create more durable experiences of digital consumption in Cluster 3 rely on the use of the same physical garment (tee-shirt) that can activate different filters automatically via AR and be transformed digitally to update the style and the digital contents (Carlings). Some examples allow a more durable digital experience by creating digital wardrobes for archival, resale, and reuse of digital garments (ARdrobe). Further, although materials, shipping, and returns are eliminated, digital garment consumption retains its carbon footprint because of the energy consumption associated with 3DVD systems. The highest engagement achieved in retailing experiences through VR and AR technologies has

the drawback of higher electricity use because of the power required for the constant connections between mobile telephones and the cloud, networks, and cellphone towers.

In Clusters 1 and 2, digital garments function to provide custom services through digital fitting and sizing tools that can check human measurements and try on garments digitally. These technological applications influence the minimization of returns positively and digital configuration, customization, and styling services can increase the ability of users to express themselves. In addition, creative industries use these experiences to design immersive virtual environments, thus shaping a new cultural universe, the Metaverse, around the brands and consumers that provide new values and meanings (Inversion, ObsessAR, Anamxr) and enhance customer experiences and potentially motivate new sustainable behaviors as well.

### Sustainability in the production stage

The digitalization of the production processes in Cluster 3 affects both environmental and cultural sustainability as using digital models of garments cuts stockholding and overproduction. Further, the process of adaptation, manipulation, and customization to body size supports the cultivation of diversity and identity. In Cluster 3, companies create new roles and job profiles (e.g., digital tailors, AR/VR/MR experts) which increases social and economic sustainability.

In Cluster 2, the production-on-demand assisted by artificial intelligence (AI) and associated with the presentation of digital garments to consumers produces sustainability holistically. From an environmental perspective, it reduces/eliminates stockholding, overproduction, pre-consumer waste, and overconsumption of raw materials. It also affects garment prices, as it can eliminate the costs of unsold garments, define a more transparent price, and pay adequately for the work of designers and manufacturers and high-quality materials, thus contributing to healthy relations between productivity and employment. Further, it introduces a more sustainable BM, as in the case of Atacac. The preorder purchases and production-on-demand based upon the customization of digital previews of fashion items necessitate and drive a cultural and behavioral shift from the consumer perspective by enhancing the customization of garments to promote diversity and self-expression. Moreover, the reshoring of garment production on a local scale with controlled, durable, environmentally-friendly materials and managed quality of the workforce has positive outcomes with respect to environmental sustainability because the supply of long-distance materials and

labor is eliminated. Finally, it affects social and cultural sustainability positively through the more equitable and ethical treatment of the workforce and the cultural reappropriation of local manufacturing activities. Traditional manufacturing processes and techniques are interpreted from a new contemporary/digital perspective with the possibility of enhancing their innovative effect by integrating tradition synergistically.

## Discussion

Analysis of the data collected in this study was based on the logic of inductive reasoning using a grey-literature review that allowed us to obtain insights into the effects of 3DVD technologies on processes, products, and BM innovations. The insights presented in the foregoing section primarily represent "the voice" of the companies which tend to view digitalization as a method that creates opportunities to generate digitally-transformed processes and positive sustainability outcomes. The emerging affirmative perspective is attributable to the novelty of the phenomena, as companies are in the early phase of commercializing digital technologies, as well as the prevailing industry discourse that digitalization is a "silver lining" to enable recovery from the adverse consequences of the COVID-19 pandemic and to achieve sustainable development in the fashion industry (Business of Fashion and McKinsey & Company 2020). In contrast, there are already some preliminary research results predicting limitations and criticism of 3DVD approaches in the fashion industry in relation to sustainability.

The grey literature shows that the adoption of 3DVD technology by the fashion industry unleashes new opportunities in products/services innovation as well as makes it possible to optimize operational processes to streamline and compress (design phase in Clusters 1, 2, and 3), eliminate (presentation B2B phase in Cluster 3), shorten time (Clusters 2 and 3), and reorganize operational models (repositioned manufacturing and retailing phases in Clusters 2 and 3) (Figure 3).

The use of 3D software changes the design process and associated methodologies and permits better and faster communication among different departments and professionals which increases the creative opportunities to achieve sustainable approaches. 3DVD design processes facilitate the ability to work across designated disciplinary domains and to enhance collaborative and transdisciplinary knowledge and hybrid design practices to increase creativity and innovation (Marshall and Pengelly 2006). Accordingly, both soft and subject-specific skills are needed to shape resilient digital
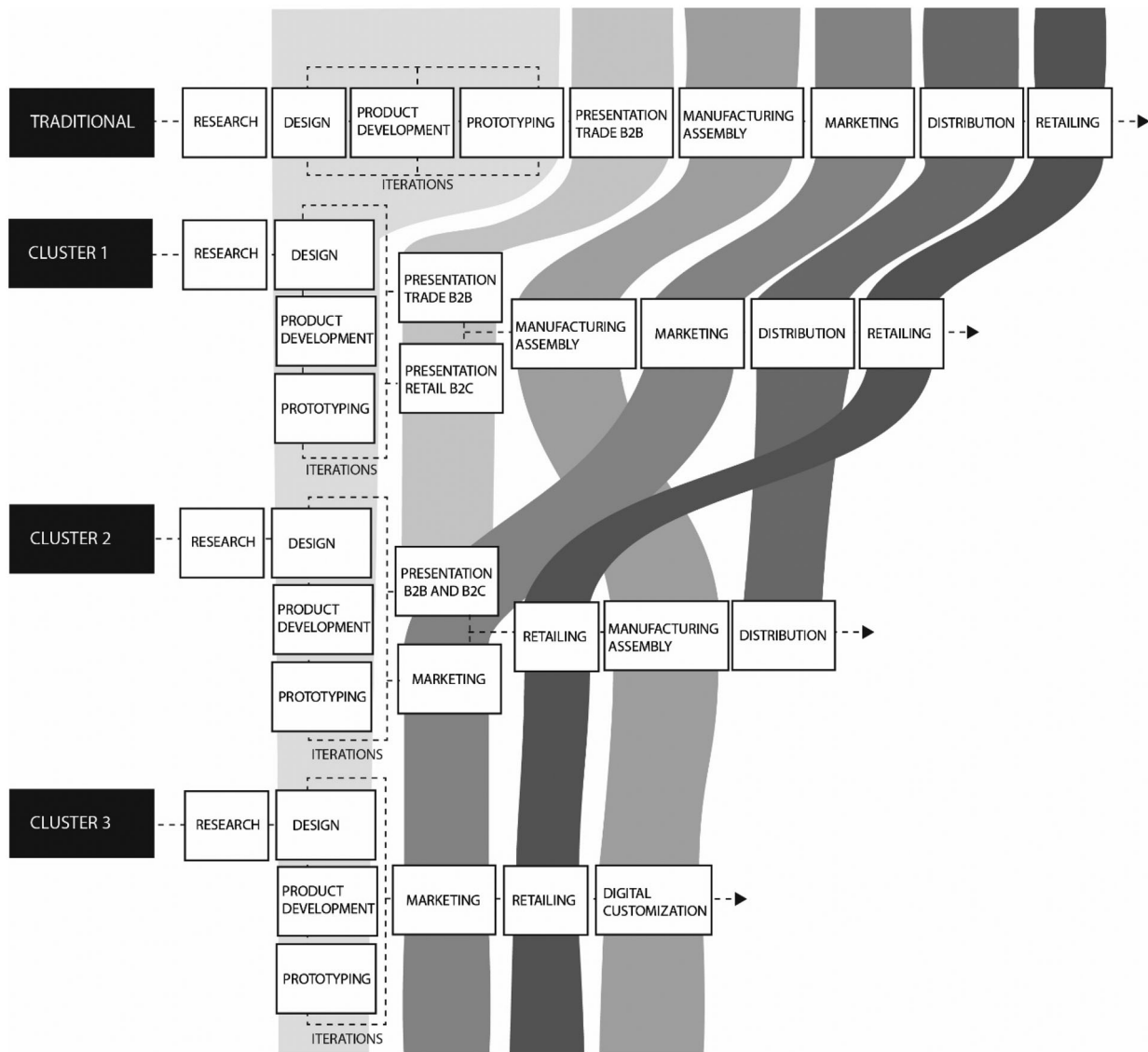
**Figure 3.** Map of traditional supply-chain model vs. supply-chain model informed by 3DVD technological transformation.

professionals. On one hand, companies today are searching for new hybrid professionals with combined digital, fashion, and business backgrounds (Kalbaska and Cantoni 2019). 3DVD technologies in fashion have motivated universities to plan to include 3DVD fashion design-related courses in their educational models (Ftalliance 2020) to train future professionals in the fashion-tech domain. On the other hand, firms in the industry that embrace the digital transformation risk job obsolescence of their workforce because of more demanding, digitally-based, and complex skills over manual skills, which causes vertical and horizontal skill mismatch, gaps, and shortages. Therefore, job-transition opportunities will be required to help workers engage in digitalization through participation in continuous education to update their skills. Digital fashion education introduces the dual topic of accessibility: 3DVD design processes require a laptop, Internet connection, and a 3D-software license that demands financial resources and a suitable infrastructure. By

contrast, digital fashion's open-source philosophy allows greater access to learning data shared across the digital fashion community (Särmäkari 2021). The innovation potential in using 3D modeling in design processes remains underexplored but appears to expand and enrich the porfolios of more explorative digitally-born companies (Clusters 2 and 3). 3DVD design guides decisions to achieve sustainability in styles, materials, shapes, and sizes in the initial design phase, and thus influences the remainder of the value chain in timing, efficiency, and costs. 3DVD design also simplifies the application of zero-waste design techniques, supports the use of innovative pattern-making approaches, and expands the opportunities to apply made-to-measure design approaches. Although, on one hand, these developments can increase opportunities for designers to participate in manufacturing processes, on the other hand, digital fashion may decrease their haptic and material knowledge (Atkinson 2017). Thus, further studies should focus on testing the effects of 3DVD

technologies in the design processes to understand their benefits and limitations with respect to feasibility, creative freedom, and design timing.

The design and development processes that occur in virtual environments allow streamlined activities and thus reduce costs. The creative process remains virtual until the manufacturing stages which changes the digitalization of wholesale trade and marketing communication. Further, processes and timing are reduced, for example, in Cluster 3, where wholesale activities have been eliminated because of the disintermediation effect of digital communication and sales tools as companies refer directly to final customers. Firms in Cluster 2 use the same digital tools, platforms, and experiences to approach different stakeholders (e.g., buyers, retailers, and final consumers). The emergence of interactive, digitally-based platforms changes the pace and modalities of fashion communication and dissemination and encourages fashion companies to change and enhance their fashion-media role (Cantoni et al. 2020). In contrast, Cluster 1 companies still display a very conservative attitude and introduce 3DVD technologies in specific processes without exploiting their full potential to achieve a complete digital transformation. Several small and niche companies (Cluster 3) are pioneering 3DVD technologies in end-to-end processes, including digital and virtual communicating tools and processes in all the steps of the workflow of the company. They show an interesting systemic approach that exploits the potential of 3DVD technologies through the digital transformation of the entire manufacturing life cycle and the creation of real-time virtual duplication (digital twin) of the entire system to promote a radical sustainable transformation (Bertola and Teunissen 2018; Bertola 2021). Digital processes and garments are used to change the physical world, both helping and disrupting physical products in the production and sales phases.

The production-on-demand approach coupled with 3DVD technologies affects the shift between the retailing and manufacturing phases (Figure 3). In Clusters 2 and 3, customers can configure their products and purchase a personalized experience based upon a preliminary digital visualization that becomes an actual unique product through digital data management and tracked logistics. Mass customization and production-on-demand typically favored through digital platforms allow personalization in style, color, size, and other preferences and pass through co-design processes between customer, retailer, and manufacturer (Maldini 2017), resulting in new business-to-business-to-consumer (B2B2C) business models (Mingione and Leoni 2020). In addition to the style, body scanning and digital application eases the adoption of production-on-demand, as customers can include their measurements to perfect the fit of the garments. Maldini et al. (2019) show that garments co-designed digitally and produced-on-demand lead to longer product lifespans because of the attachment that users have to their enhanced emotional and functional values. Some cases in the greyliterature review (e.g., Atacac, Dressarte Paris) show this pioneering approach in delivering co-designed services and experiences to manufacture garments with a personalized fit and style with which users feel an emotional connection that thereby affects the longevity of the garment.

Digital garments ease data replication, conversion, manipulation, and recombination, and thereby support the democratic cultural remix of information and products (Brennen and Kreiss 2016). The digitalization of the retailing phase includes the digitalization of products into their digital twins, the coupling with digital services, and the provision of new experiences incorporated into the purchasing processes. Sensorial and valuable storytelling in the experience is essential to recover the loss of information attributable to the dematerialization of products that provide visual, functional, and behavioral simulations of product attributes through zoom, 2D or 3D rotation, and virtual try-on with avatars via 3D or AR visualization that allow consumers to evaluate the items online more effectively and to overcome the relative sensory impoverishment compared to bricks-and-mortar retail. New design opportunities can emerge to overcome the limitations inherent in the ability of digital technologies to offer the physical and tangible experiences of materials to reveal their flow (weight, thickness, drape), movement (stretchiness, comfort), fabric-tactile feature (hand or feel of fabric such as softness, smoothness, and voluminosity), and details (stitching and seams) in the digital domain (Ornati 2021, 2022).

3DVD technologies appear to drive multi-centered BM innovations that affect changes in all three value-architecture dimensions. The cloud-based, service-oriented platforms that deliver digital fashion products and services (B2B/B2C customization/personalization) represent a radical BM innovation. This allows for breakthrough improvements in value co-creation and delivery (via a network and user/community-oriented approach) and provides new revenue streams as well. Because of the digital BM innovation associated with the virtualization of product contents, the borderline between fashion, entertainment, gaming, and arts is becoming blurred, representing a shift from "fashion as a service" to "fashion as a lifestyle." Further, it offers the

ability to simultaneoulsy create economic, environmental, and societal/cultural benefits. Previous research on digital BM innovations has mentioned the shift toward platform model and service, network, and user/community-oriented approaches (Noris et al. 2021; Ibarra, Ganzarain, and Igartua 2018; Teece and Linden 2017; Bharadwaj et al. 2013). Gregori and Holzmann (2020) also demonstrated that digital BMs create opportunities for socio-environmental value creation via more resource-efficient and faster processes, involvement of customers/communities in value co-creation, and network effects in platform-business models. Whether digital technologies have positive implications for multidimensional sustainable value creation and thus contribute to sustainable development depends upon the nature of the socio-technical transition. The way technology is used depends upon the values, objectives, resources, practices, and policies that accompany the firm and stakeholder adoption of technologies.

The analysis revealed that 3DVD technologies affect all four dimensions of sustainability that are interconnected intrinsically throughout supply-chain processes (Figure 4). Cultural sustainability is of paramount importance because fashion is a complex cultural system that creates products and services that affect the environment, economy, and society. The results of the analysis indicated that the technological effect on design processes, production, and retailing brings about significant transformational changes in a company's organizational culture and consumers' cultural systems. In particular, new creative approaches in the design phases can be applied to disrupt traditional working modes and standardized production processes to achieve sustainability and innovation. Moreover, digitalization allows the rigid limitations in sizing and pattern construction to be overcome and opposes the secretive ways in which the fashion sector works to produce new open knowledge through an increase in collaboration, transparency, inclusivity, and democracy derived from customization opportunities. The digital transformation that occurs in the preliminary design stages shows that a real cultural effect can be achieved only if the entire supply chain is affected to sustain, promote, and deliver its full innovative potential.

3DVD technologies enable the digital conversion of "disposable fashion" in the virtual world and provide opportunities to have a positive effect on the environment and enhance the self-expression of
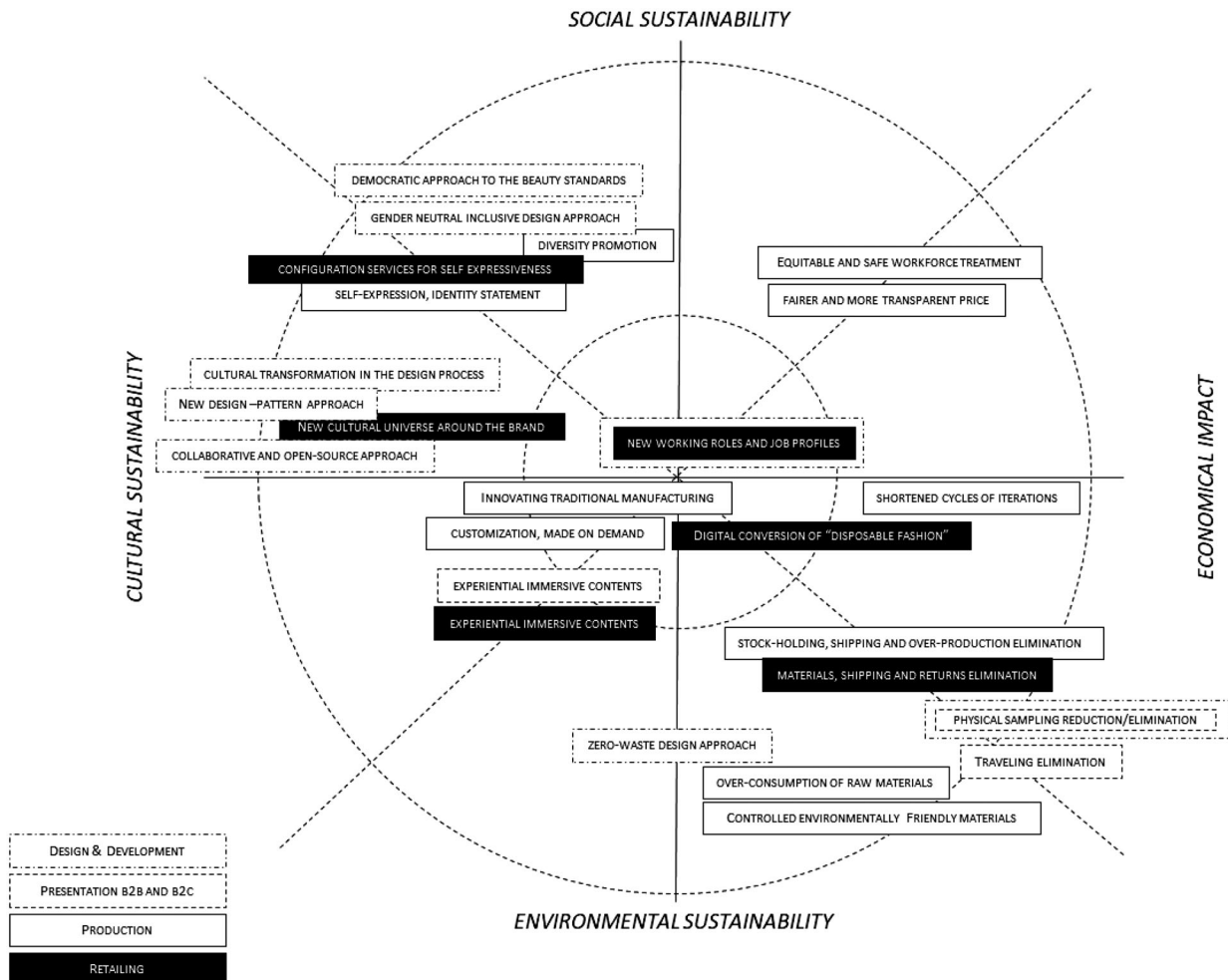


Figure 4. Map of 3DVD effects on the four pillars of sustainability through the supply chain.

individuals on social media. However, there are concerns that this will have a detrimental effect on the transformation to more sustainable consumer cultures against overconsumption habits (Crewe 2017). Instead, the outcome may be reiterated, similar to fast-fashion consumer behaviors through the social media domain. "While digitalization is already a key driving force in societal transformation, it has so far led to more consumption and inequality and remained coupled with the indirect use of energy and materials, therefore sustaining resource-intensive and greenhouse-gas growth patterns at the macro-economic level" (Wiedmann et al. 2020, 7). Only a few company cases analyzed in this study examined whether there is a fundamental cultural change among consumers of digital products/services that do not encourage the fast-paced production/waste of digital outfits used on social media but instead enhance ethical/responsible fashion-consumption behaviors.

However, the digital shift in design, production, retailing, and consumption does not suffice to conclude that 3DVD technological adoption is sustainable from an environmental perspective. The fact that garments, shows, presentations, and shops become virtual and digital does not mean that the system becomes intrinsically more sustainable as the information and communications technology (ICT) sector is a source of 1.8–2.8% of global greenhouse-gas emissions, and these values are underestimations because they fail to account for the full extent of the associated supply chain and life cycle impacts (Andrae and Edler 2015; Freitag et al. 2021). The invisible infrastructure that lies behind the programming, rendering, and digital consumption of 3DVD products accounts for the footprint of the digital fashion system (Andrae 2017). Calculations of actual environmental effects do not include the energy consumption of data centers, networks, and blockchain transactions, the specific architecture of which (proof-of-work vs. non-proof-of-work) determines greater/lighter environmental effects (Sedlmeir et al. 2020). Because the trend of the energy efficiency of ICTs indicates that the carbon footprint will not decrease, designers, policy makers, entrepreneurs and common users should undertake proactive decisions and responsible behaviors to limit their environmental effects. In addition, because of the Jevons' Paradox (Jevons 1865), the increase in system efficiency creates higher consumption levels if consumer behavior and lifestyles are not addressed at their core. Therefore, sustainable digital and valuable fashion experiences for customers need to be supported by a sustainable design approach that interfaces with the experiences of users on the digital platforms. The intangible cultural values of companies through storytelling and the effects of technological choices on consumption levels and patterns should be considered when seeking to design sustainable 3DVD-based fashion experiences along the entire supply chain.

## Conclusions and future research agenda

This article provides a systematic overview of digital transformation in the fashion industry by mapping the effects of 3DVD technologies on the traditional fashion supply-chain model onto the four dimensions of sustainability and BM innovations. The structural shifts identified in the fashion industry that are attributable to digitalization create the following opportunities.

- Dematerialization of the supply chain with respect to improving resource efficiency and compressing, eliminating, and shortening various business activities, as well as reorganizing the operating model toward a more collaborative approach in different stages of the process.
- New B2B and B2C products and services with more focus on the experience and engagement of users (e.g., digital garments and cyber-fitting services, physical garments augmented with VR filters that provide the opportunity for constant updating, virtual B2B presentation, wholesaling, and design services).
- Network-, community-, and service-/experience-oriented BMs that offer the opportunity for simultaneous value creation along multiple dimensions of sustainability, in which platform-based services emerge as a new digital BM archetype.
- Studies of the innovation potential of 3DVD technologies in the design processes with respect to new methodologies and approaches to achieve creativity and sustainability.
- Investigations of the multiple dimensions of sustainability with a primary focus on the cultural pillar to design 3DVD technological products/services that can radically change the consumption behaviors of consumers to reach a more ethical/responsible paradigm.

The comprehensive overview in this article aims to facilitate multidisciplinary dialogue among fashion practitioners. To reach the promise of sustainable digital transformation to dematerialize resource-intensive, design-driven practices of the traditional fashion industry the application of digital technologies should be considered simultaneously at various design levels including:

- Product design to foster sustainable/valuable user experiences and lifestyles.

- Process design that considers the interconnections along the entire supply chain to realize shared value co-creation and sustain innovation.
- BM design to ensure that investments in the adoption of digital technologies capture value.
- Integrate sustainability design thinking into all of the above, including the cultural aspects.

Stemming from the results of this article, we provide research directions toward sustainability and innovation paths in the digital transformation of the fashion industry that could engage the interest of both academics and practitioners. A critical research study might focus on the environmental effects of 3DVD technologies throughout the fashion-supply chain compared to the traditional chain. Such a study should focus on the energy consumption of ICT-based services including computing devices, data centers, and communication networks involved in the full digital process because the existing literature has investigated this issue only in part or not focused specifically on the fashion sector. Future research can address the missing systemic approach to sustainability. Comprehensive sustainable assessment models should be applied through a blended approach that includes the cultural dimension when considering complex phenomena. Another line of research could focus on the limitations of 3DVD technologies to study the full potential of end-to-end applications as several examples have shown the systematic application of digital technologies in all supply-chain processes. Understanding socio-technological drivers and barriers to the digital transformation of the supply chain from the back-end to frontend will provide relevant insights into systemic preconditions that need to be created at the individual, corporate, interorganizational, and policy levels to anchor the digital transition to innovation and sustainability.

Dematerialization of supply-chain processes and products offers the ability to make more informed design decisions to disrupt traditional and standardized logic. Further exploration could focus on the creative exploitation of technologies to modify the way garments are inspired (e.g., AI through data management and data science to inform sustainable choices and innovation), conceived (e.g., pattern-making explorations to achieve fit and sustainability), perceived (e.g., tactile and haptic experiences), and the ways in which digital BMs are designed (e.g., sustainable user experiences and value propositions).

Finally, digital transformation that addresses the systemic application of digital technologies is related to closing the digital capabilities gap by allowing access/developing relevant resources and skills (Teece and Linden 2017; Pal and Sandberg 2017). The companies included in this study have demonstrated the diversity of organizational configurations necessary to acquire these resources, capabilities, and skills, from integrating digital competencies internally to acquiring them externally, and from initiating digital startups as spin-off new organizations to launching cloud-based service-oriented platforms. Therefore, exploring the factors that affect the digital organizational design aspects of BMs represents another future research direction.

## Notes

1. Digitalization is defined as adoption or increase in the use of digital technologies that affect the economy, society, and culture and enable a business transformation in operations, functions, models, processes, and activities (Brennen and Kreiss 2016).
2. Digitization is defined as the material process of conversion, interpretation, storage, and transfer of analogue streams of information such as images, video, and text into a digital form (Negronponte 1995; Brennen and Kreiss 2016).
3. Bridging Asia and Europe, Turkey in 2020 was the fourth largest textile and garment manufacturer and exporter in the fashion industry (Statista 2022). Working today in a global context as supplier and subcontractor of the international luxury and fast fashion industries, many Turkish companies have already embraced the shift of their design and prototyping activities to a digital and virtual approach, being involved in the Industry 4.0 transformation to be more productive and competitive and to increase and accelerate communications with their stakeholders (Tokatli 2003; Gökalp, Gökalp, and Eren 2019).

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